Trajectory Specification for Terminal Air Traffic: Pairwise Conflict Detection and Resolution

Russ Paielli and Heinz Erzberger
NASA Ames Research Center

AIAA ATIO Conference
Denver, CO
June 8, 2017

Outline

- Background
- Trajectory Specification
- Conflict detection
- Conflict resolution
- Pairwise conflict test method
- Results
- Concluding Remarks

Introduction

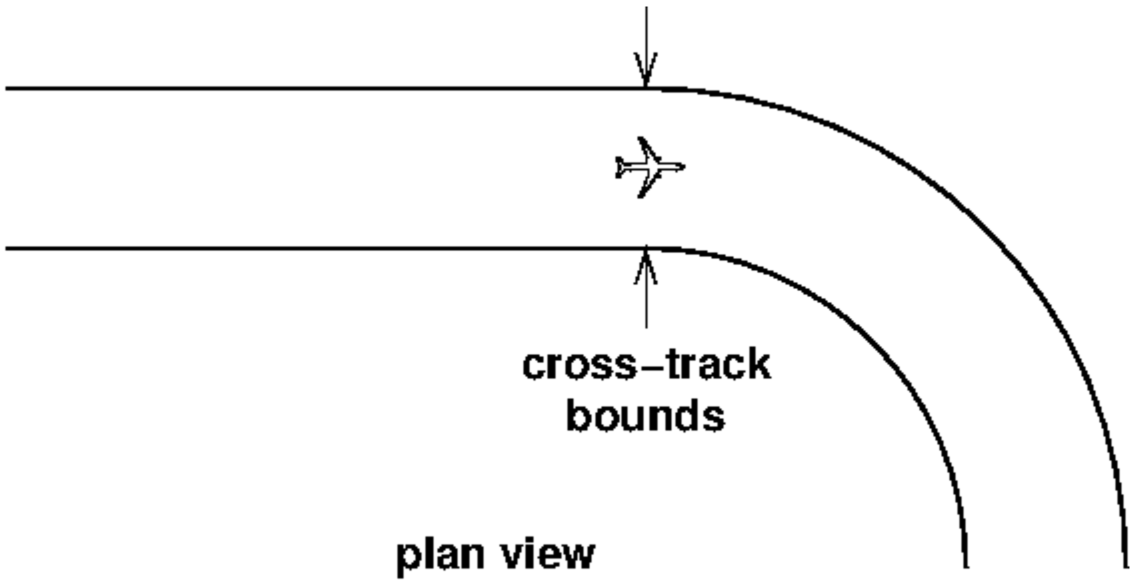
- NASA is developing the Advanced Airspace Concept (AAC) to automate ATC
  - Applies to both enroute and terminal airspace
  - Goes beyond decision support to enable eventual autonomy (little or no human intervention)

- Trajectory Specification is an enhancement of AAC
  - Has near-term application for trajectory prediction error modeling, but
  - Full concept is far-term because it requires new FMS (Flight Management System) standards

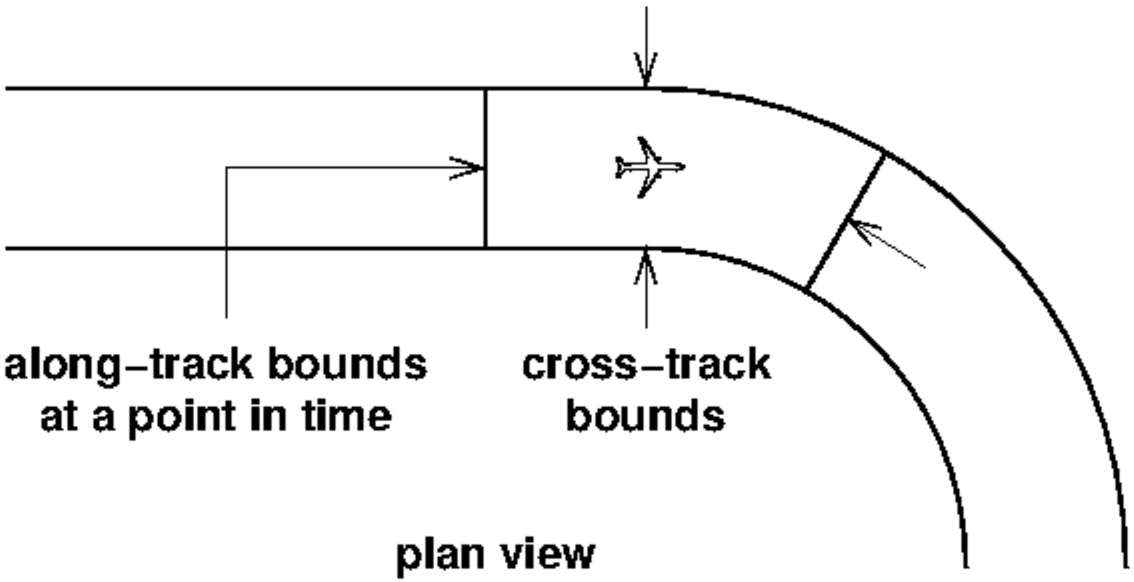
Trajectory Specification: Dynamic “4D” RNP

- Required Navigation Performance (RNP) is based on published routes with fixed cross-track bounds and real-time conformance monitoring
- Trajectory Specification concept is dynamic and adds vertical and along-track (time-based) bounds

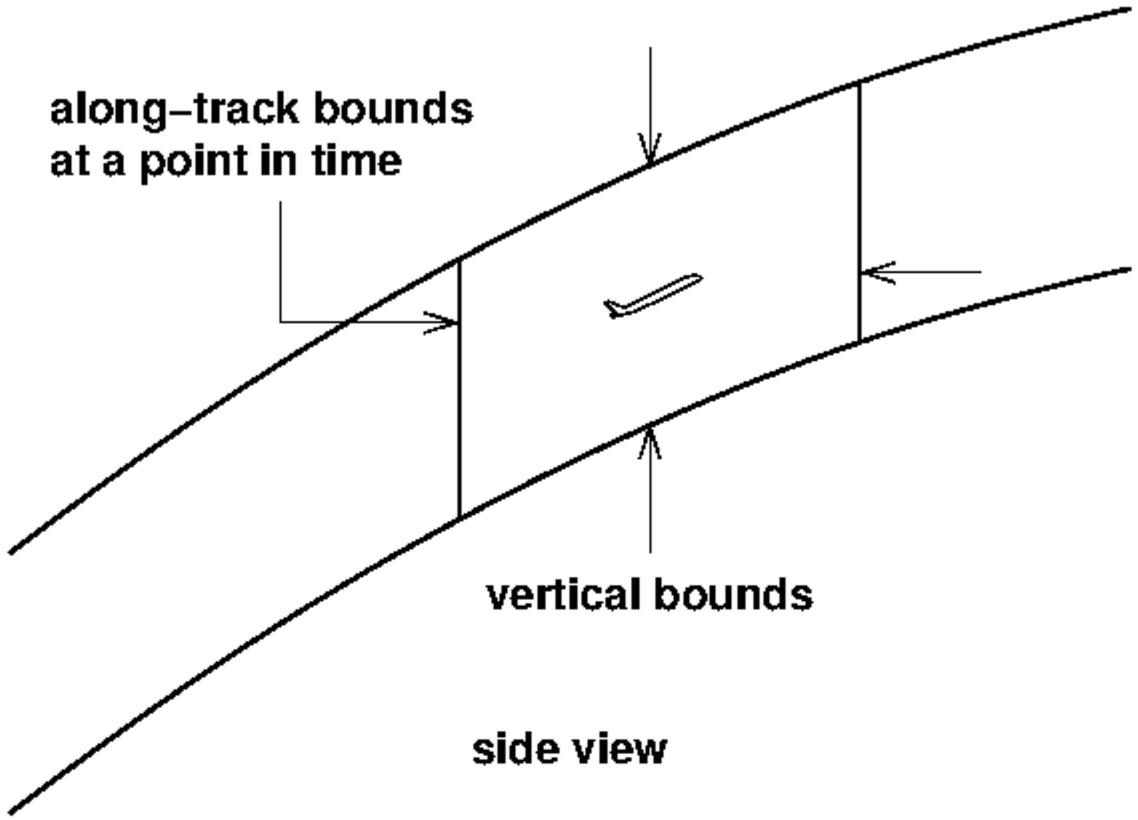
Required Navigation Performance (RNP)



Trajectory Specification: Horizontal Bounds



Trajectory Specification: Vertical Bounds



Related Concepts

- Joulia and Le Talle (2011-)
  - “4D” contract with elliptical tolerance “bubble”
  - Fixed tolerances too restrictive in light traffic
- Jackson, et al. (2009-)
  - “4D” trajectory datalink (4DTRAD)
  - Allows altitude bounds at several discrete points
  - Allows one required time of arrival (RTA)
  - Works with existing FMSs
  - Does not explicitly bound trajectory at any time

[Trajectory Specification should not be confused with another tube concept that implements “freeways in the sky”]

Trajectory Specification Features

- Each aircraft constrained to a well defined volume of space at each point in time
- Bounds determined by tolerances relative to a reference “4D” trajectory (position as function of time)
- Tolerances can be piecewise linear function of distance along route (function fixed at time of assignment)
- Tolerances cannot be less than aircraft navigational capability allows but can be as large as current traffic situation permits (without a conflict)

Challenges of Automation

- Failsafe operation required if automated system or datalink goes down (cannot depend on a human controller to take over)
- Trajectories with unbounded prediction errors cannot be guaranteed conflict-free for a sufficient period of time (depends on wind modeling error)

Trajectory Specification Benefits

- Can guarantee conflict-free trajectories for a specified period of time (assuming conformance) -- facilitates failsafe operation
- Provides more reliable strategic planning and less reliance on tactical backup systems and tactical maneuvering during normal operation

Basic Operational Concept

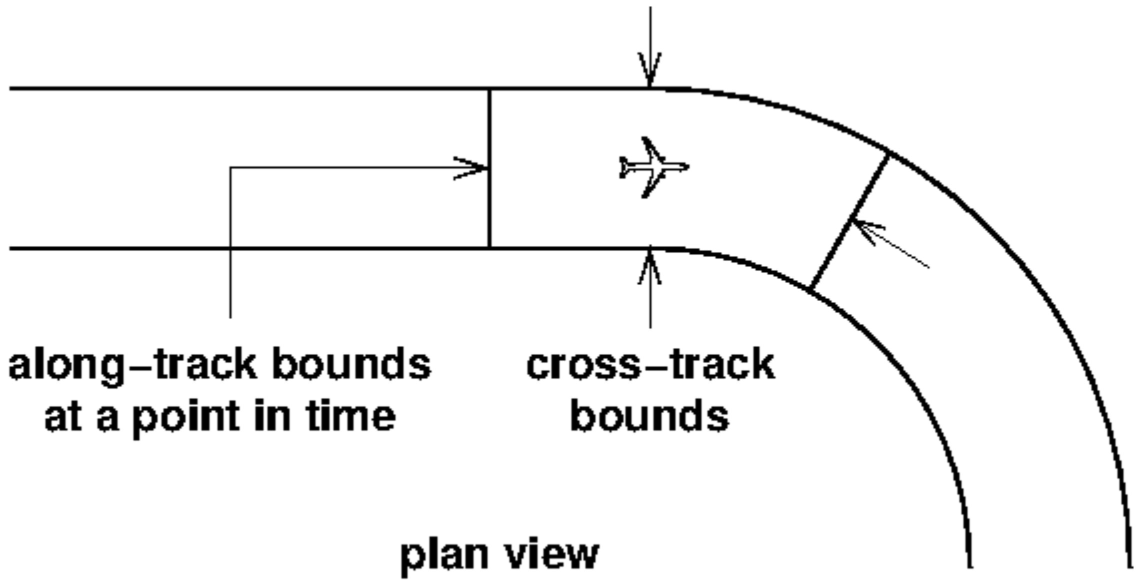
- Pilot enters route/intent into Flight Management System
- FMS computes “4D” trajectory prediction
- FMS downlinks predicted trajectory to ATC as request
- ATC assigns tolerances, checks for conflicts
- ATC modifies trajectory if necessary to resolve conflicts
- ATC uplinks assigned trajectory with tolerances
- FMS flies assigned trajectory to specified tolerances

Trajectory Specification Language (TSL) based on XML to be documented in a NASA Technical Memorandum

Objective

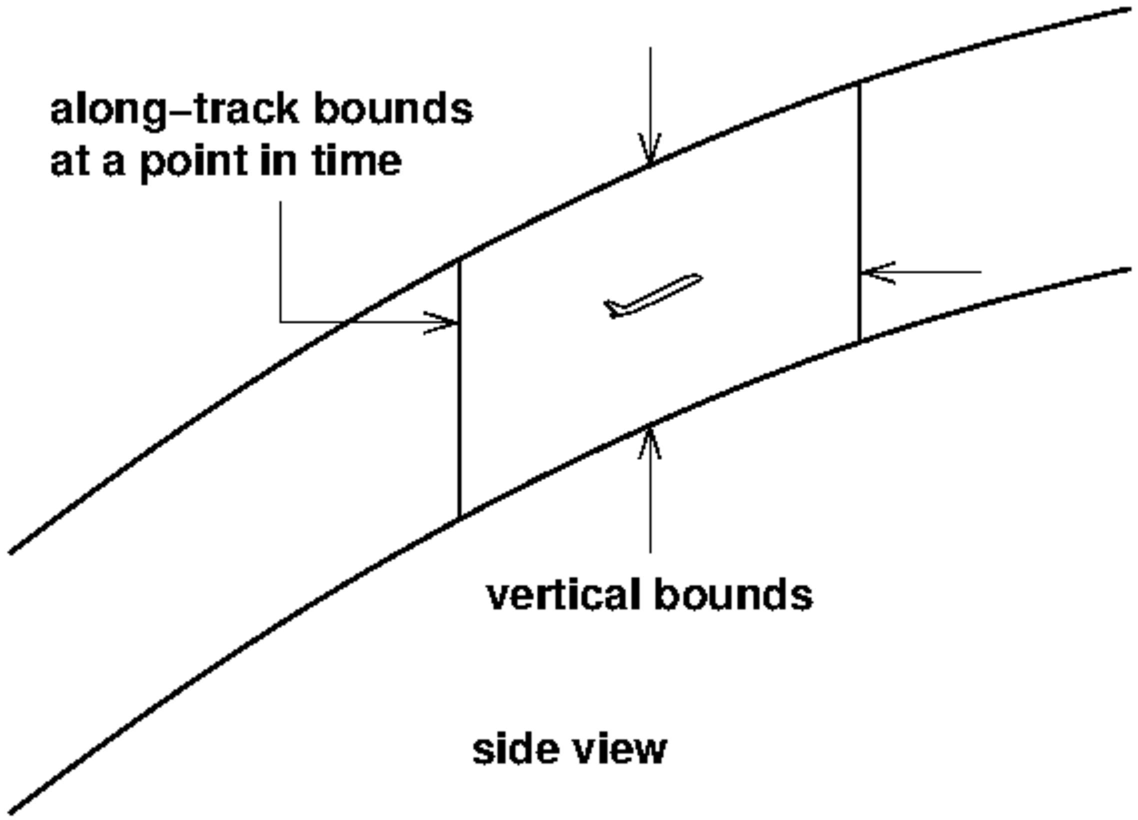
To develop a research software prototype and demonstrate the computational feasibility of Trajectory Specification as applied to conflict detection and resolution for terminal air traffic

Conflict Detection



Anywhere within the bounding space, the aircraft should be sufficiently separated from all other flights (at any point in *their* bounding space).

Conflict Detection



Conflict Detection

- Need to ensure minimum required separation for entire bounding space at each point in time
- Much more computation than simple pointwise separation calculations
- Use coarse checks and large time steps to avoid detailed computation when separation is large
- Horizontal separation of bounding areas can be calculated using polygon approximation
- When horizontal separation of bounding areas is insufficient, use gridded sampling method

Definition of Separation Ratio

Minimum separation standard:

3 nmi horizontal or

1,000 ft (1 kft) vertical

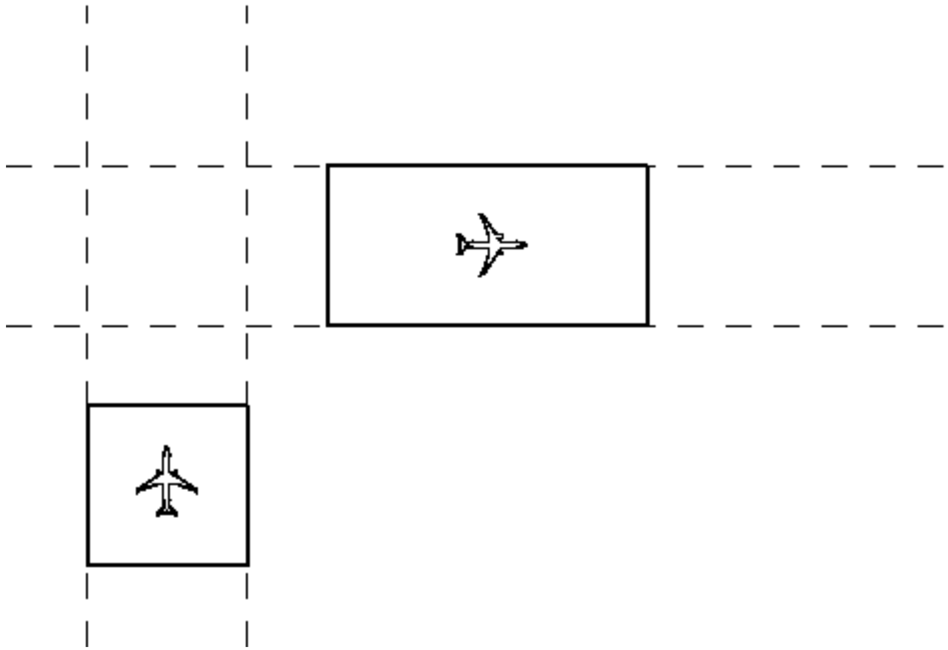
horiz sep ratio = horiz sep / 3 nmi

vert sep ratio = vert sep / 1000 ft

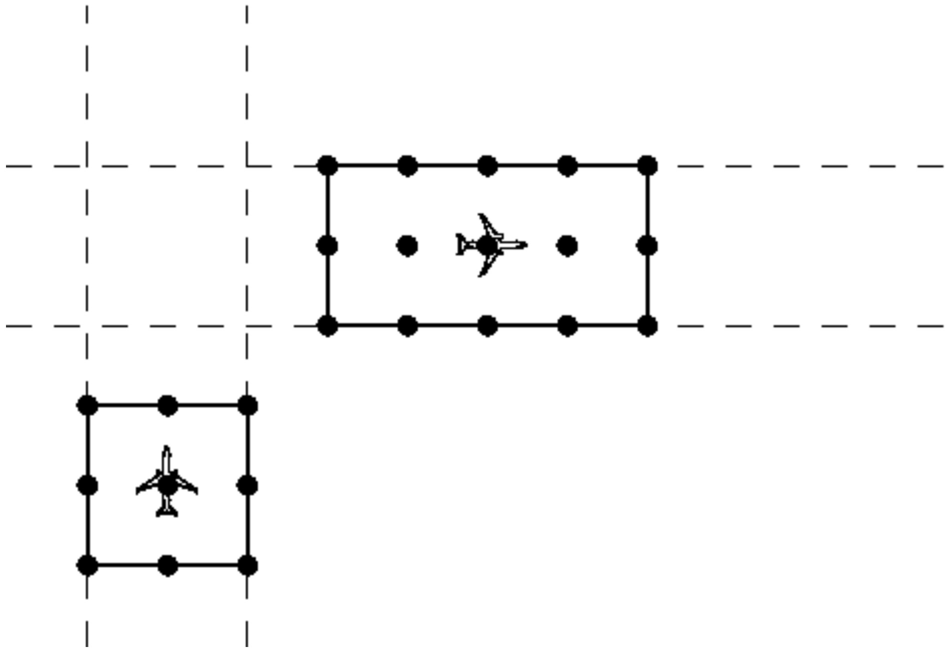
separation ratio = max(horiz, vert) sep ratio

< 1.0 means less than separation standard

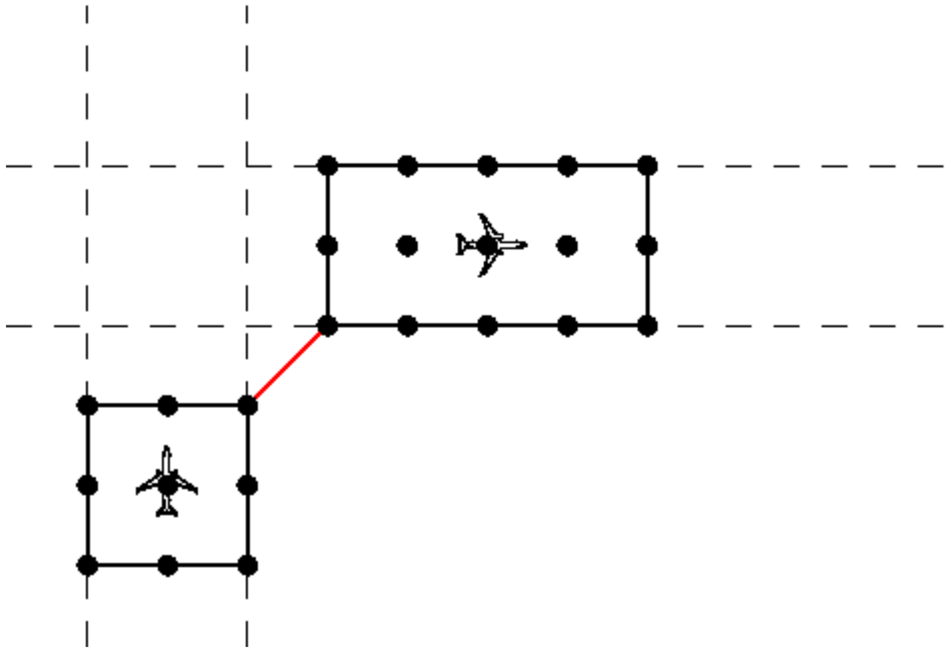
Combines horizontal and vertical separation into a single scalar metric (for comparison, ranking, ordering)



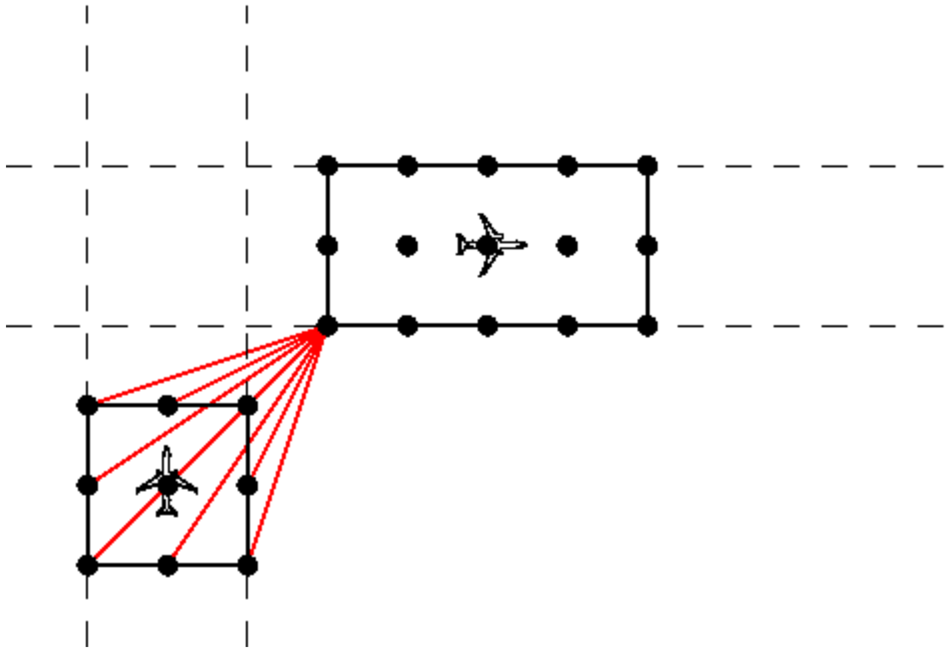
Plan view of bounding spaces at a point in time

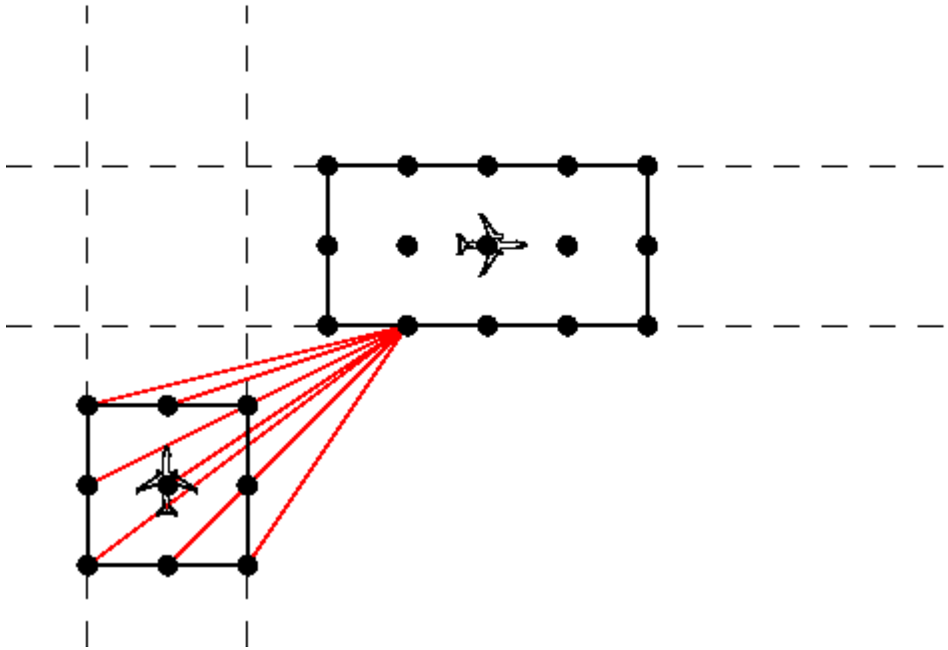


[Each grid point has an altitude range]



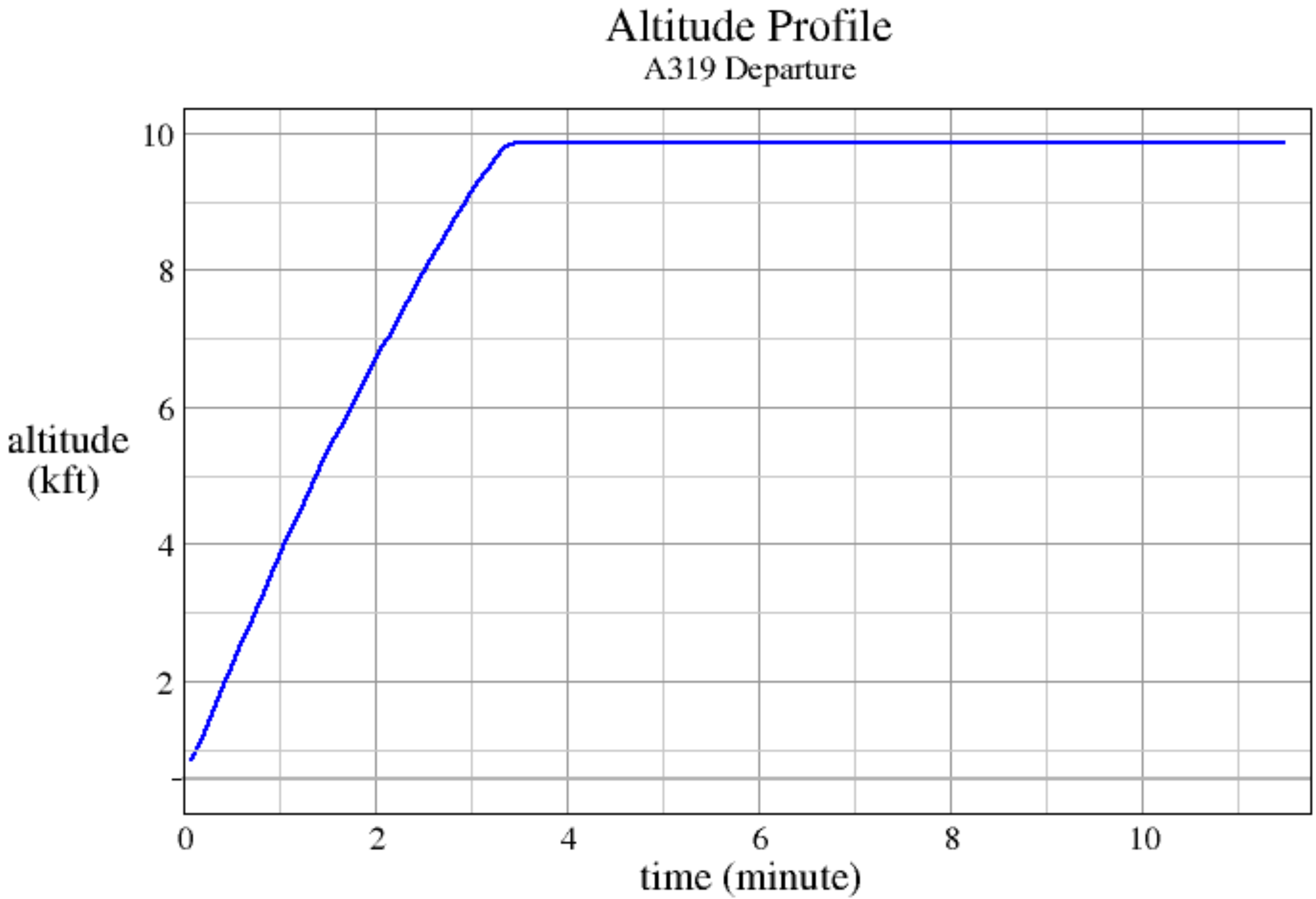
Calculate separation ratio for each pair of grid points and record minimum

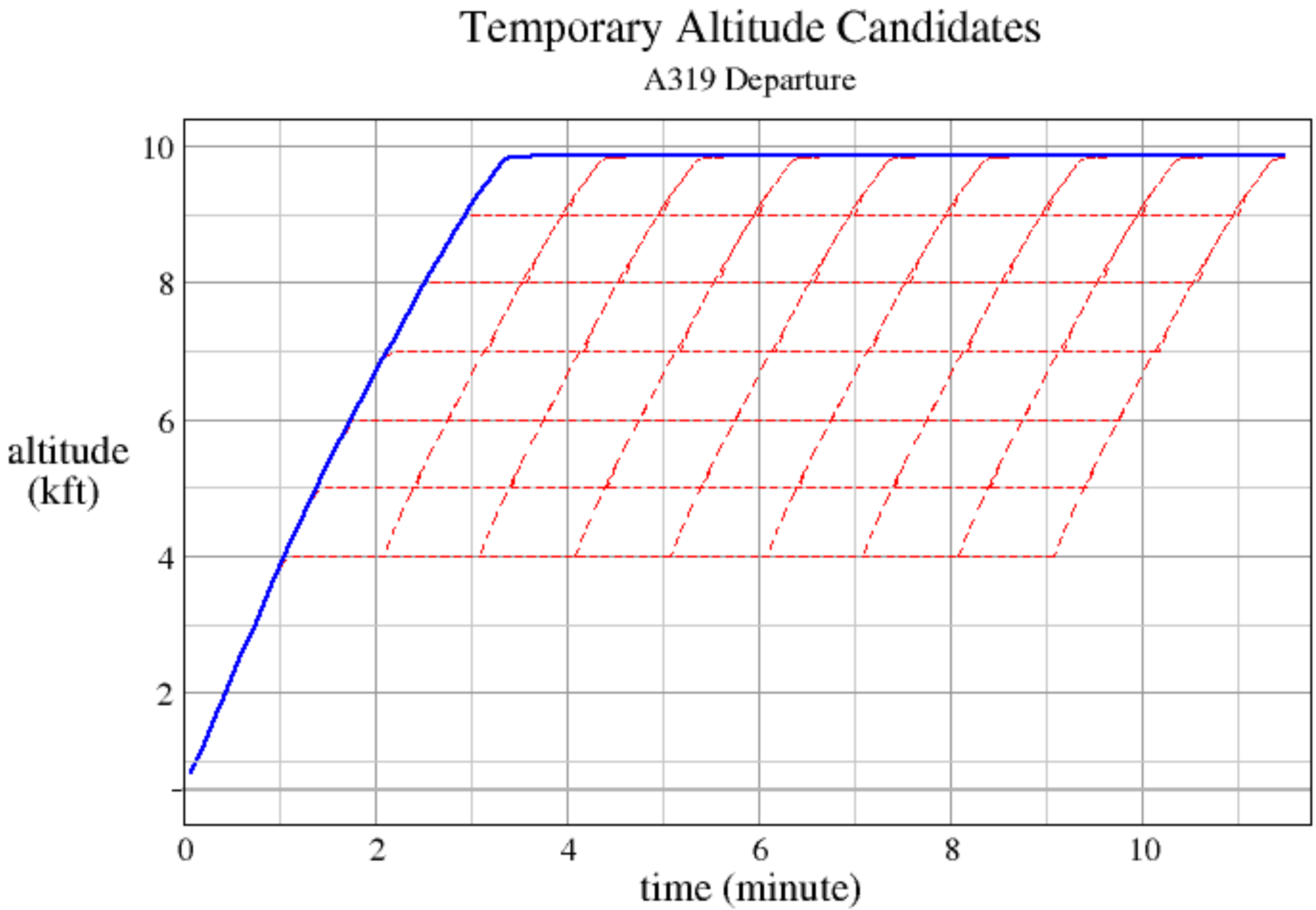


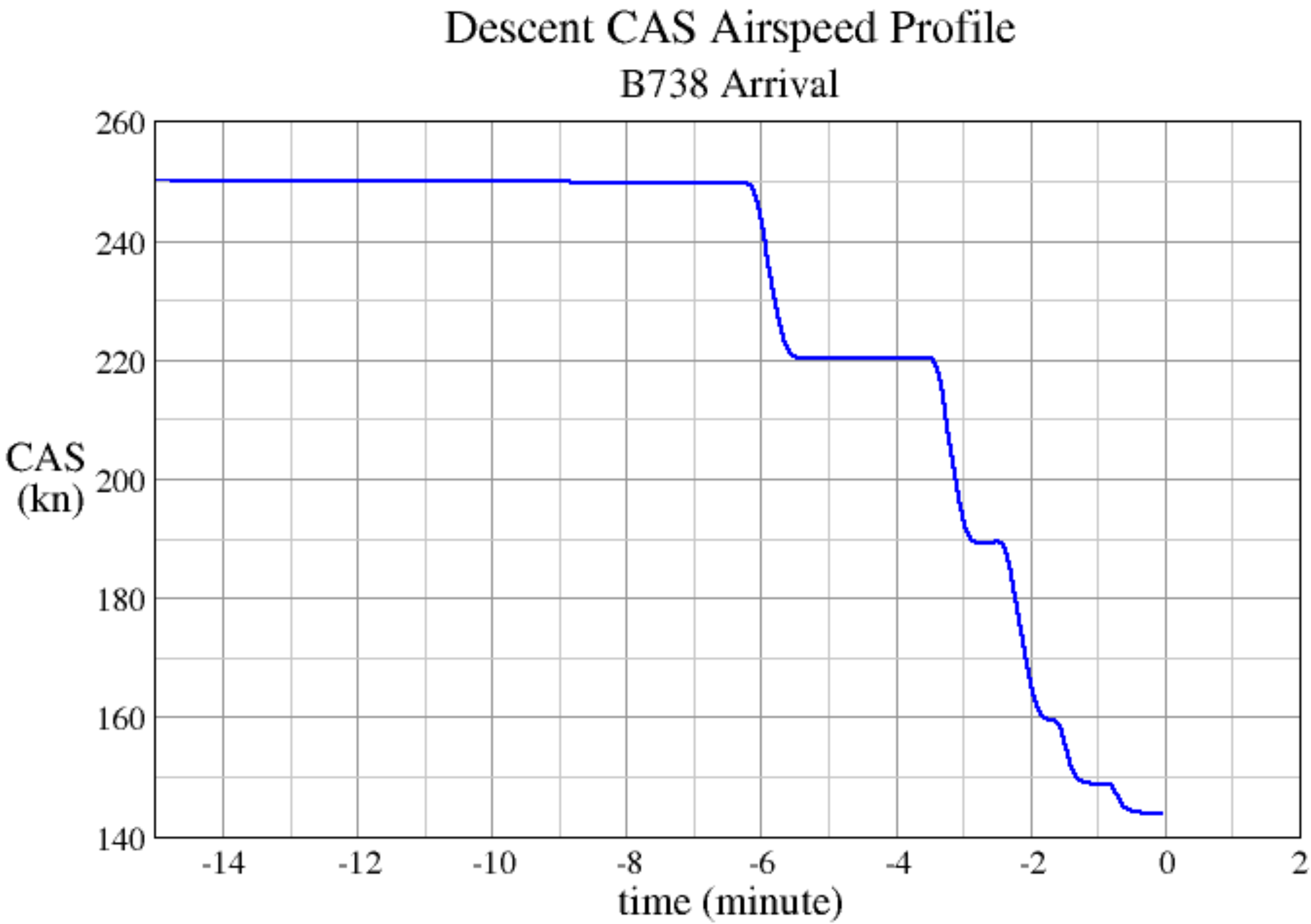


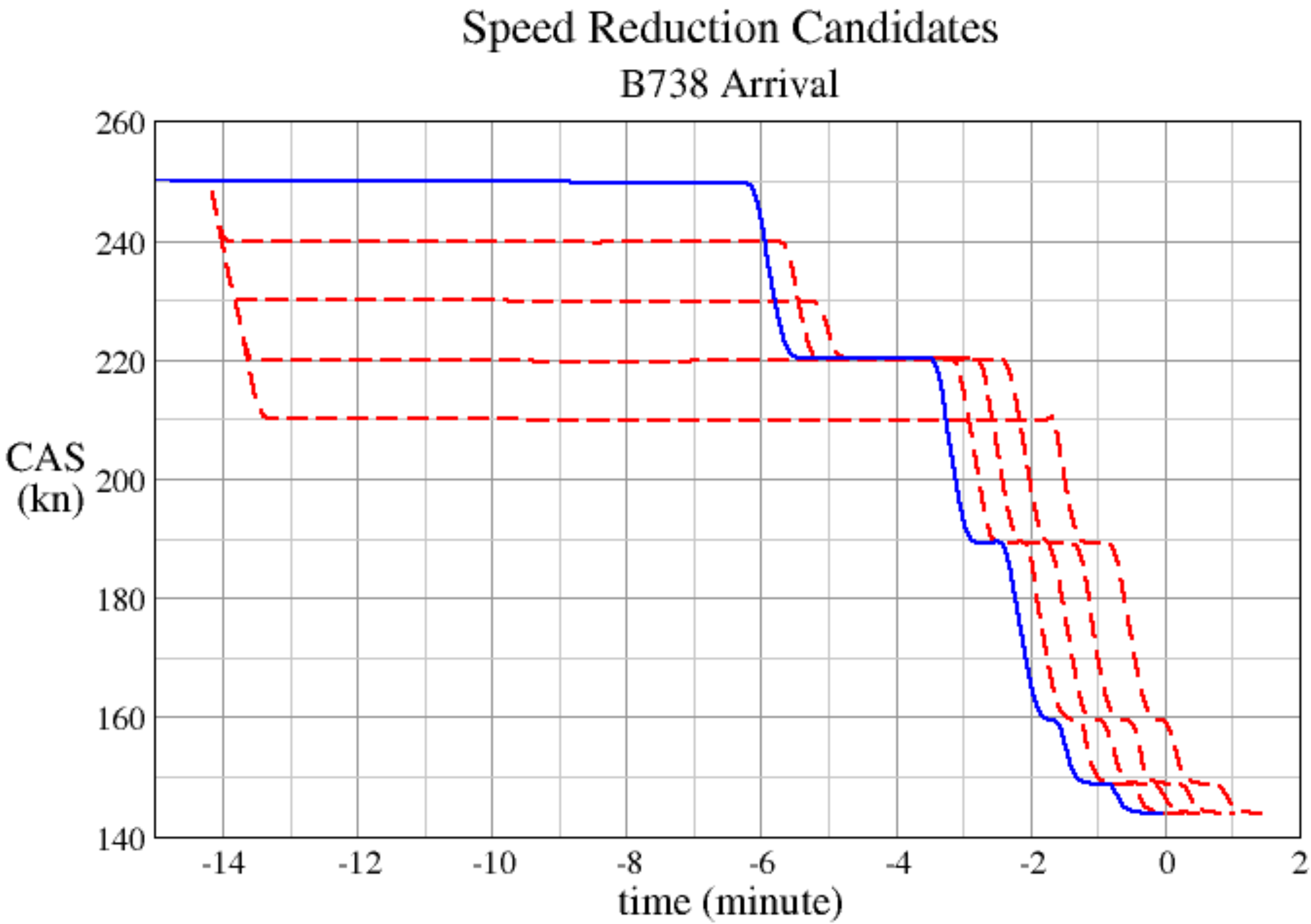
Conflict Resolution Maneuver Types

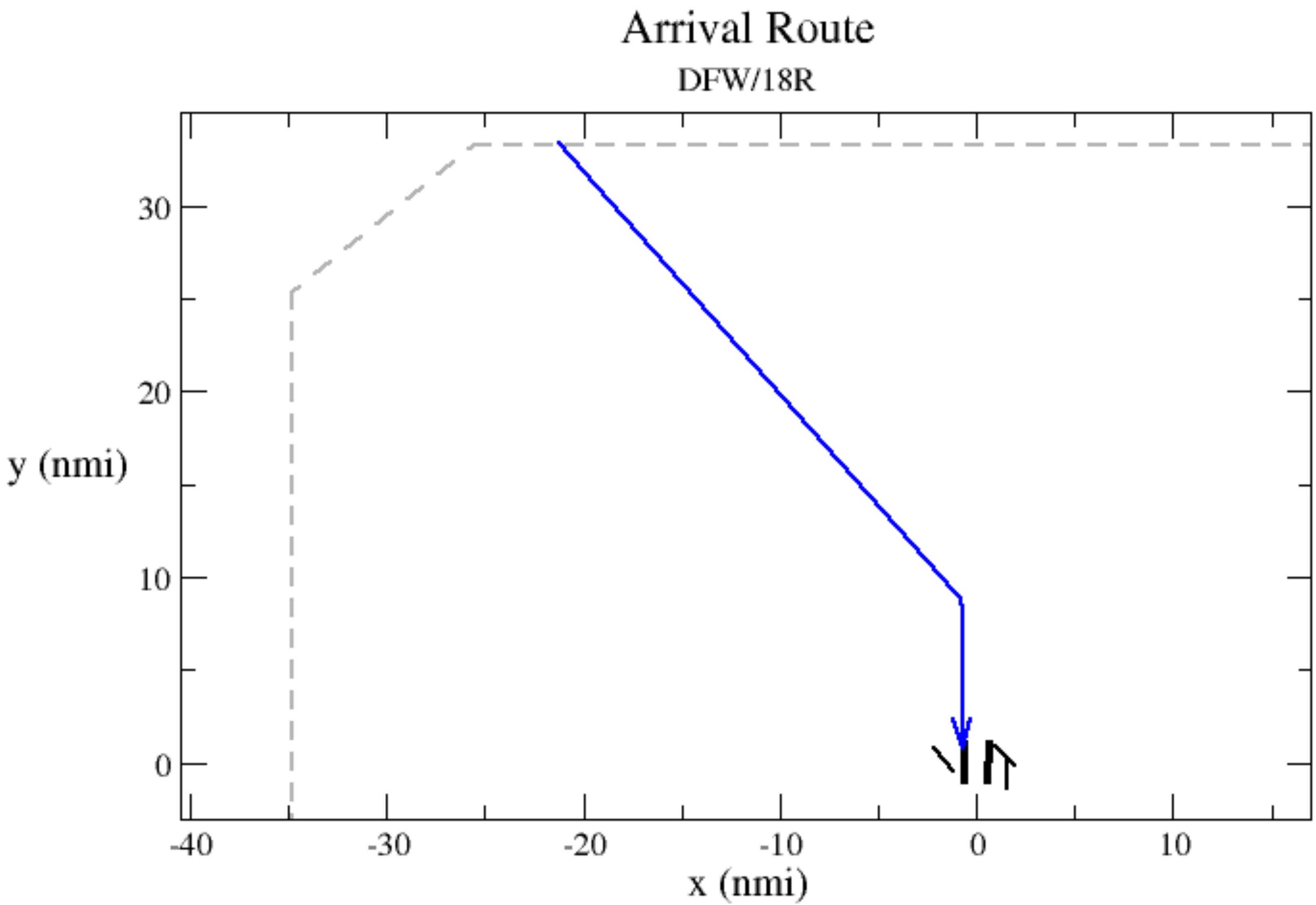
- Temporary Altitude
- Speed Reduction
- Reroute
- Takeoff Delay
- Other


Altitude Profile
A319 Departure
altitude (kft)
10
8
6
4
2
0
2
4
6
8
10
time (minute)

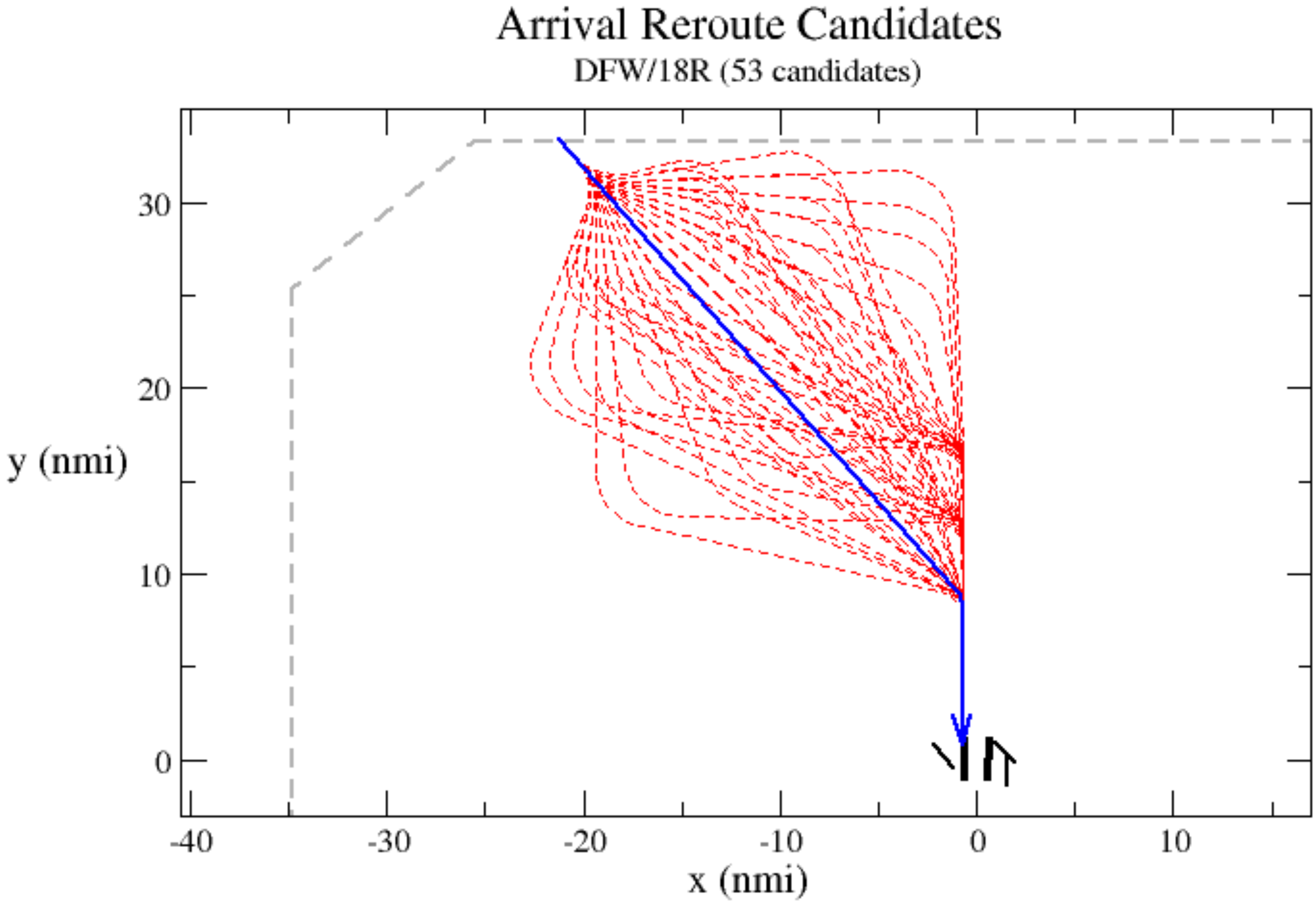

Temporary Altitude Candidates
A319 Departure
altitude (kft)
time (minute)
0
2
4
6
8
10


Descent CAS Airspeed Profile
B738 Arrival
CAS
(kn)
260
240
220
200
180
160
140
-14
-12
-10
-8
-6
-4
-2
0
2
time (minute)


Speed Reduction Candidates
B738 Arrival
CAS (kn)
260
240
220
200
180
160
140
-14
-12
-10
-8
-6
-4
-2
0
2
time (minute)



Arrival Route
DFW/18R
y (nmi)
x (nmi)
30
20
10
0
-40
-30
-20
-10
0
10

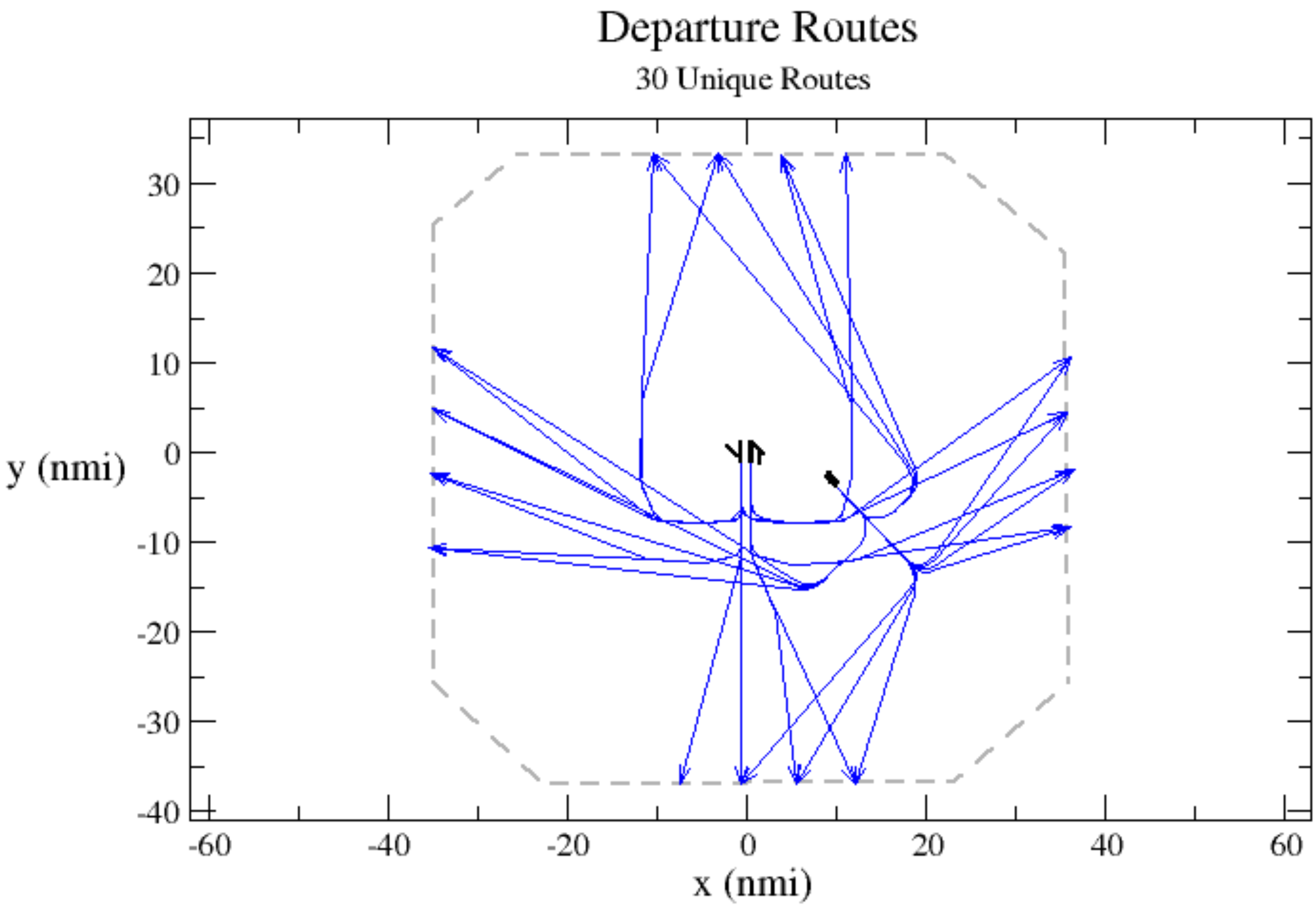

Arrival Reroute Candidates
DFW/18R (53 candidates)
y (nmi)
30
20
10
0
-40
-30
-20
-10
0
10
x (nmi)

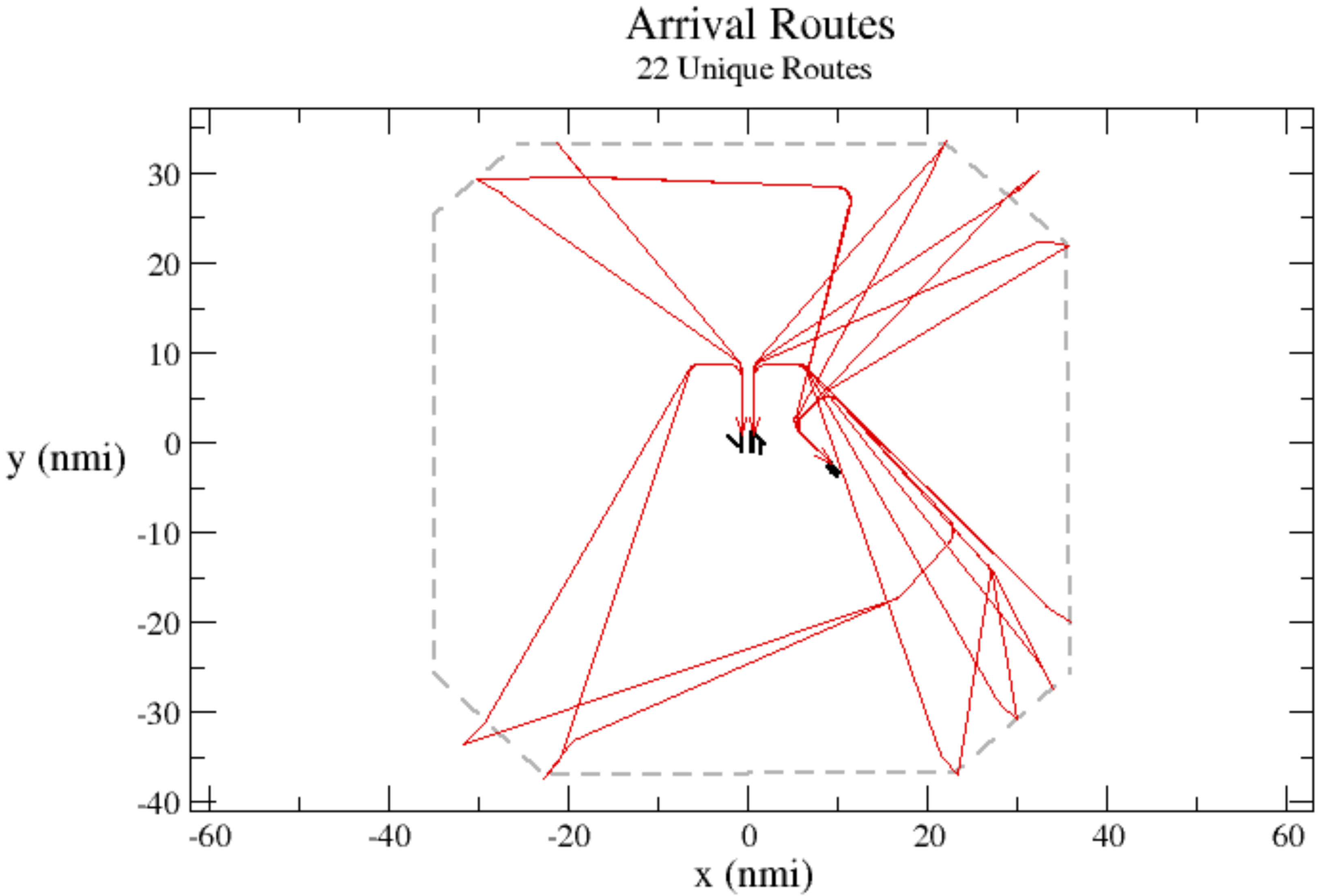
Pairwise Conflict Resolution

- Conflict resolution must avoid conflicts with all traffic
- Pairwise conflict resolution is simpler but is a logical first step
- This paper is limited to pairwise conflict resolution, but a future paper will address general conflict resolution in realistic traffic

Test Environment

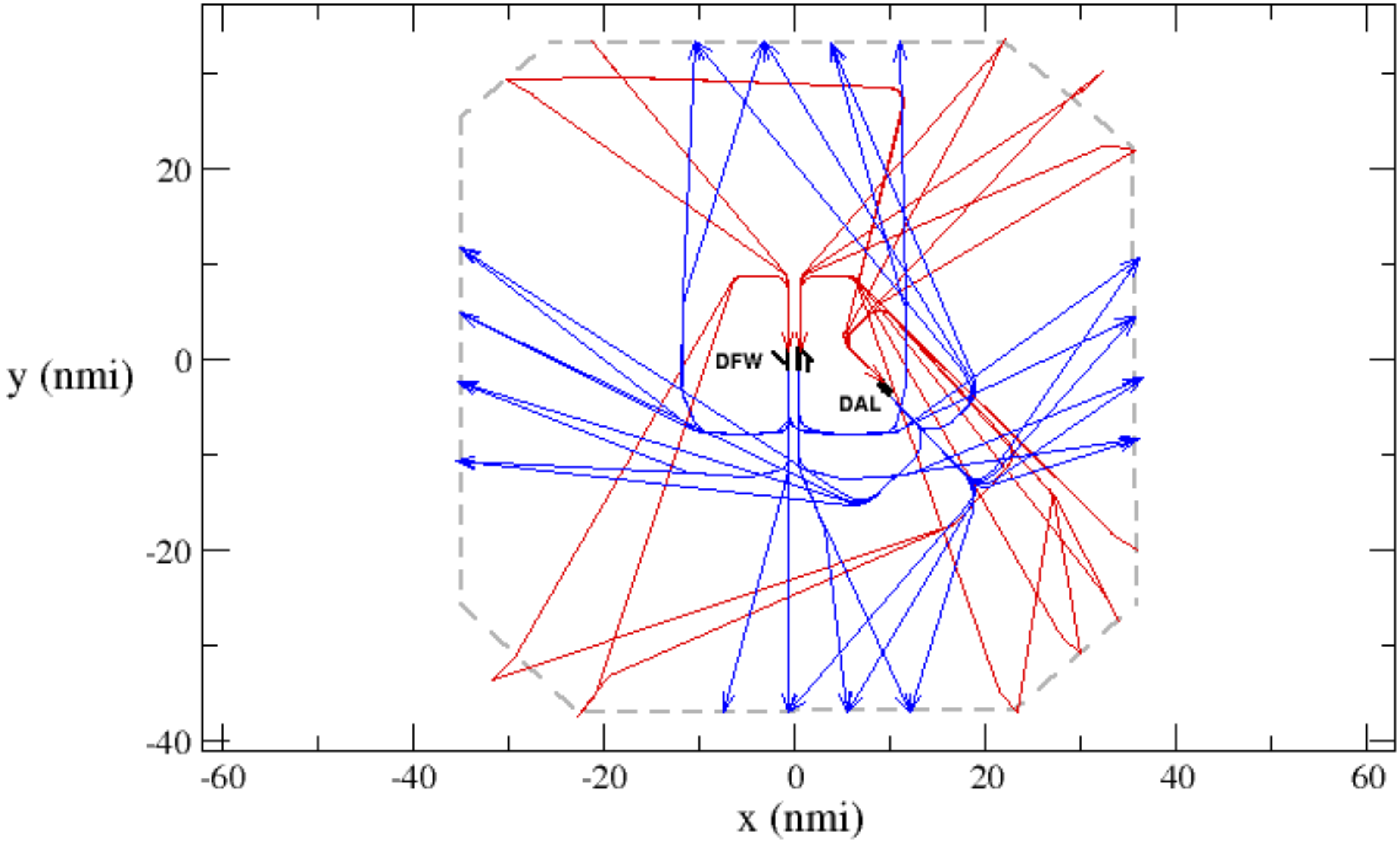
- Trajectories generated using NASA simulators:
  - Airspace Concepts Evaluation System (ACES)
  - Kinematic Trajectory Generator (KTG)
- One full day of (unresolved) trajectories generated for DFW and DAL airports
  - DFW arrivals routed direct to final approach
  - Default tolerances applied
- Trajectories modified to simulate maneuvers for resolving conflicts


Departure Routes
30 Unique Routes
y (nmi)
x (nmi)
30
20
10
0
-10
-20
-30
-40
-60
-40
-20
0
20
40
60


Arrival Routes
22 Unique Routes
y (nmi)
x (nmi)
30
20
10
0
-10
-20
-30
-40
-60
-40
-20
0
20
40
60

Arrival and Departure Routes

52 Unique Routes: 30 departure, 22 arrival

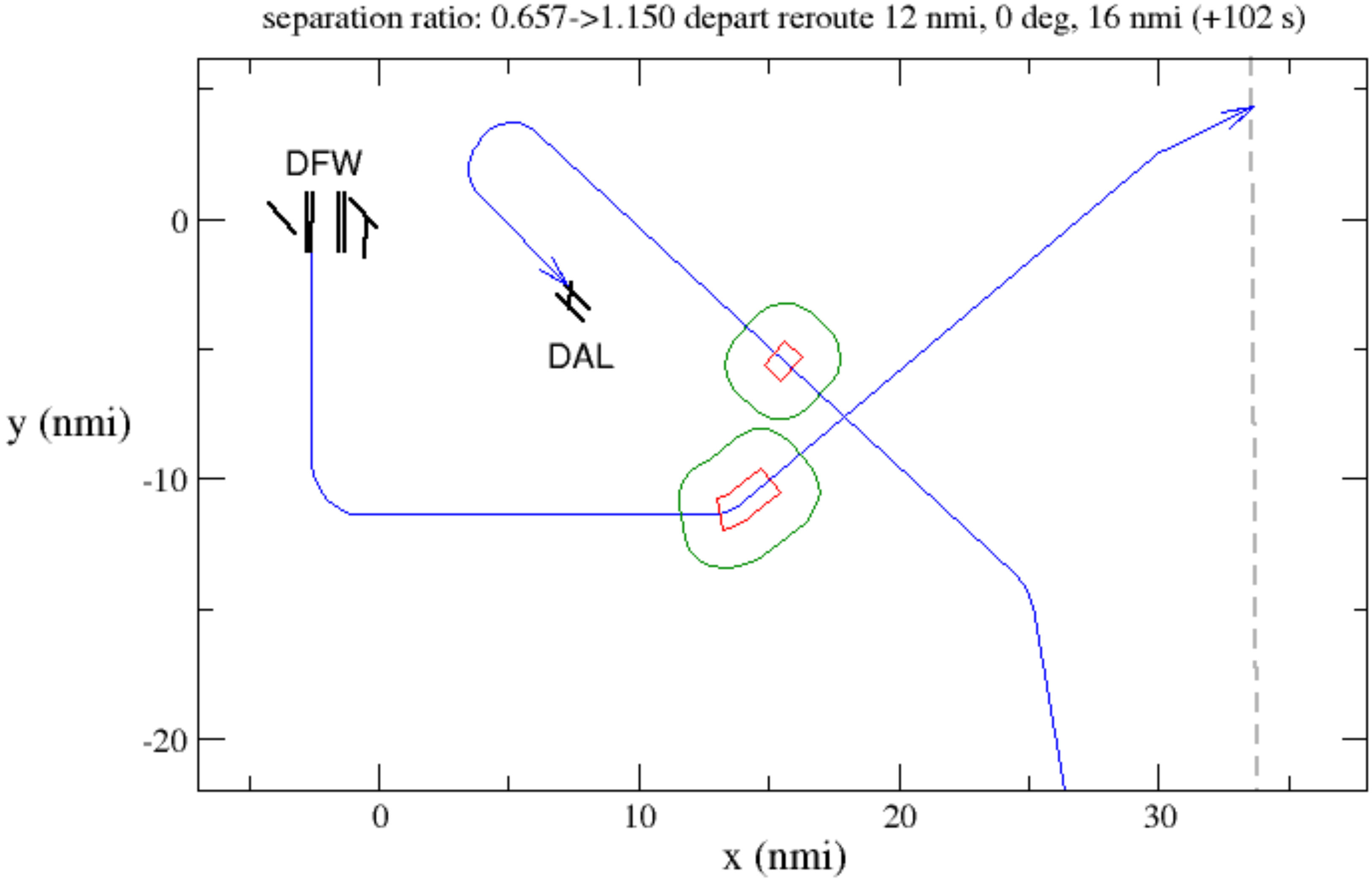


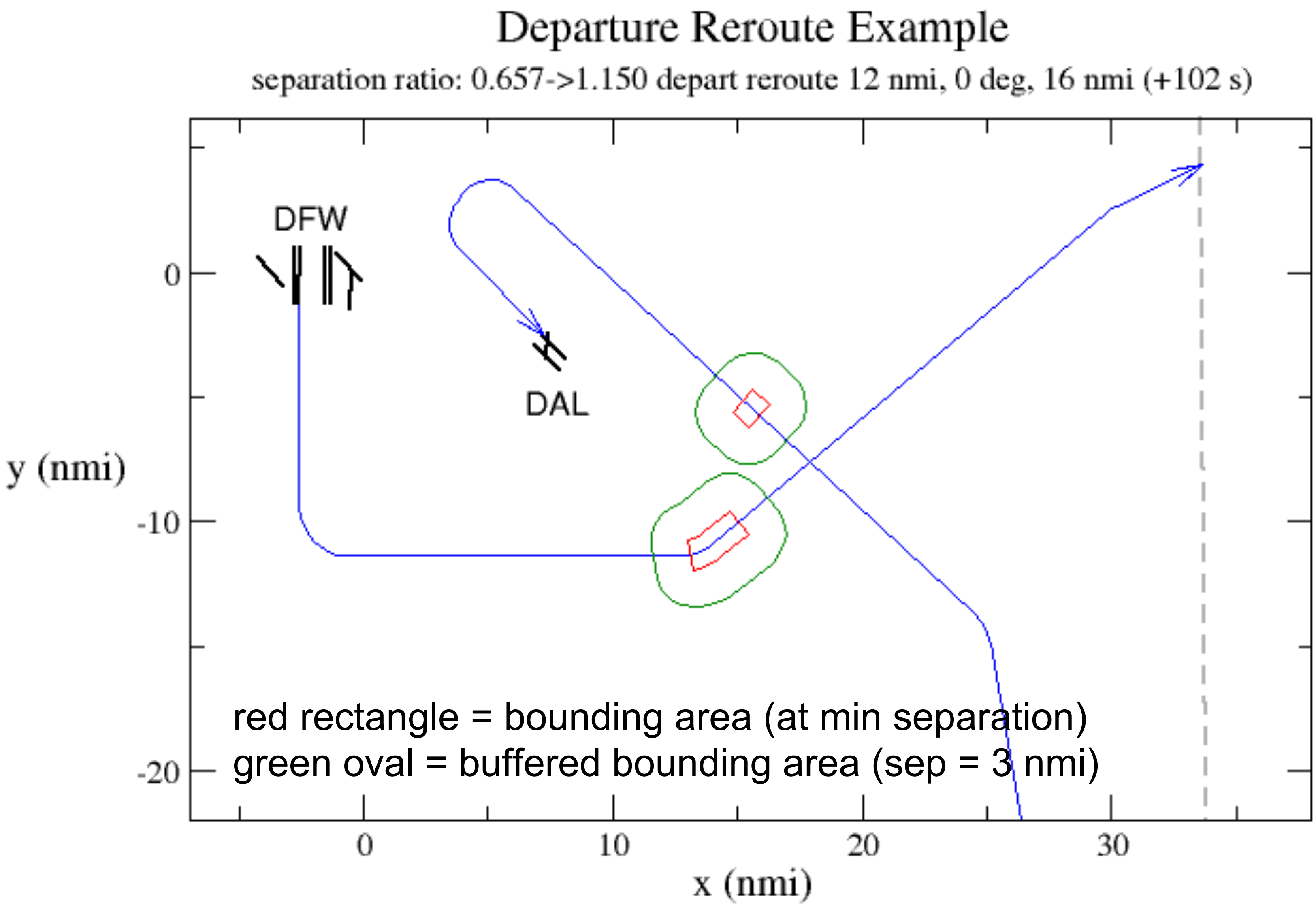
Pairwise Resolution Tests

- 52 unique routes (30 departure, 22 arrival)
- One trajectory to represent each route
- 52 x 51 / 2 = 1326 trajectory pairs
- Each pair time shifted in steps of 30 sec
- 1325 pairwise conflicts resulted
- One flight maneuvered per conflict

- All conflicts successfully resolved
- Run time < 1 sec per pairwise conflict
  (with parallel processing on an Intel 32-core processor)

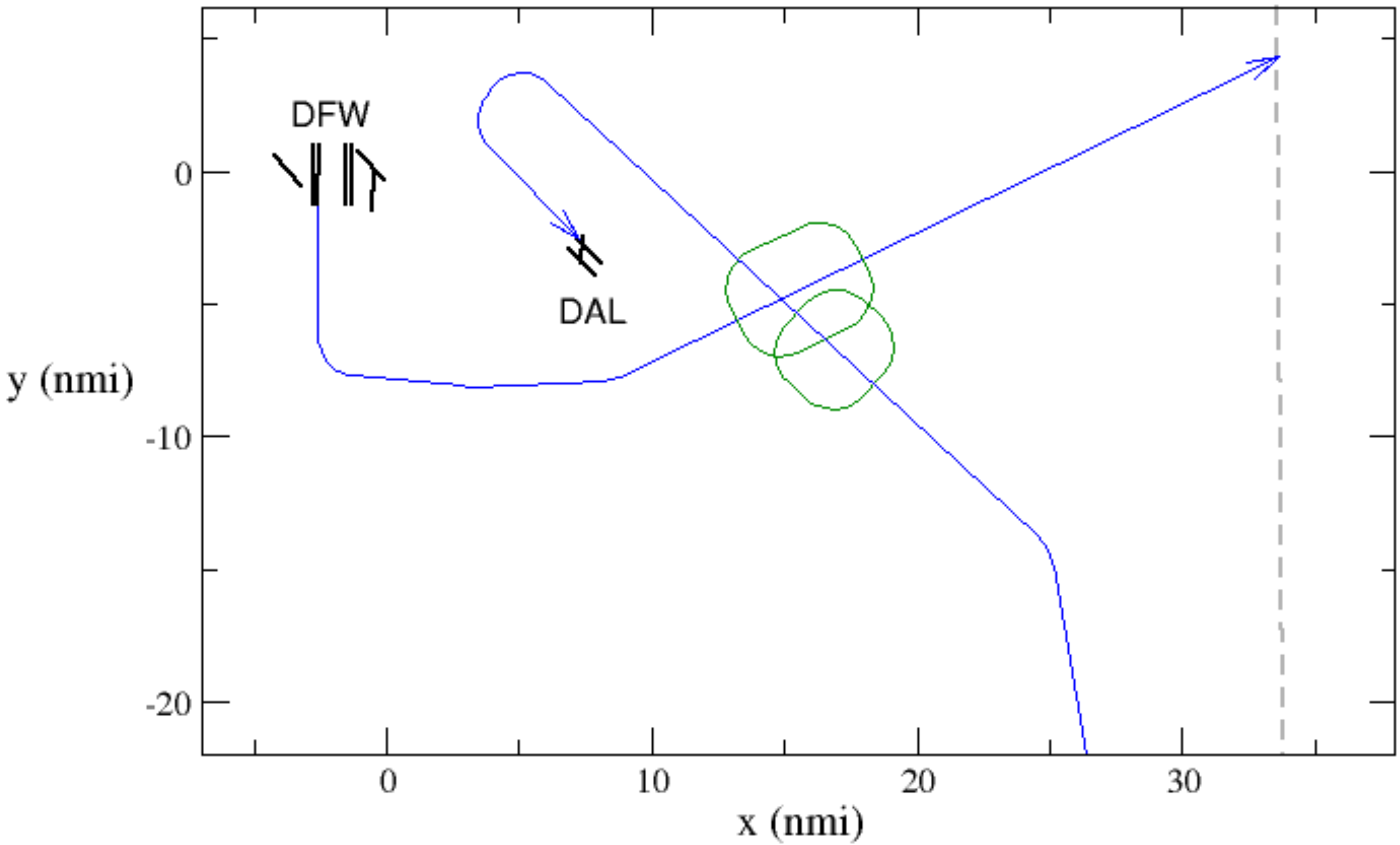
Departure Reroute Example

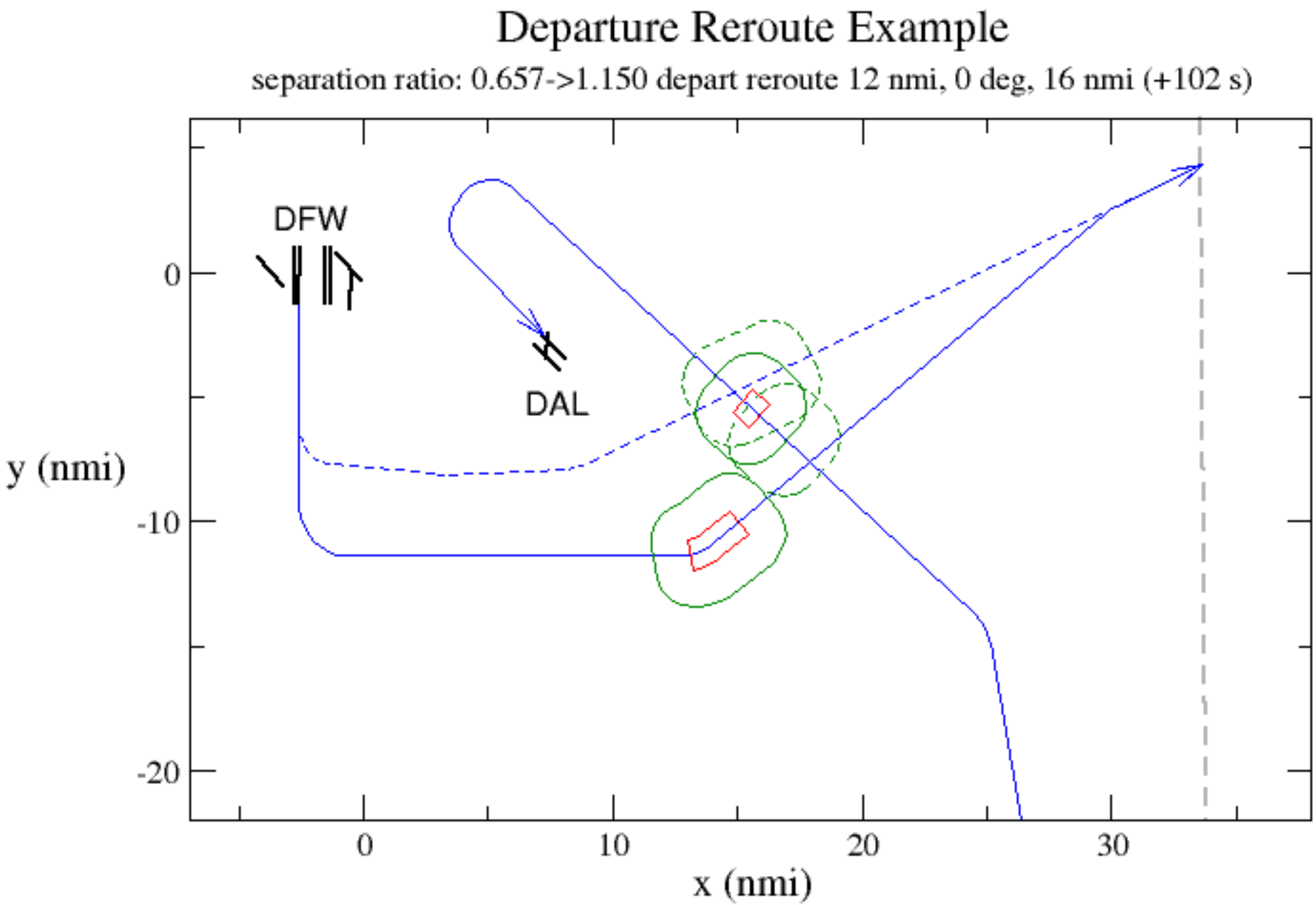


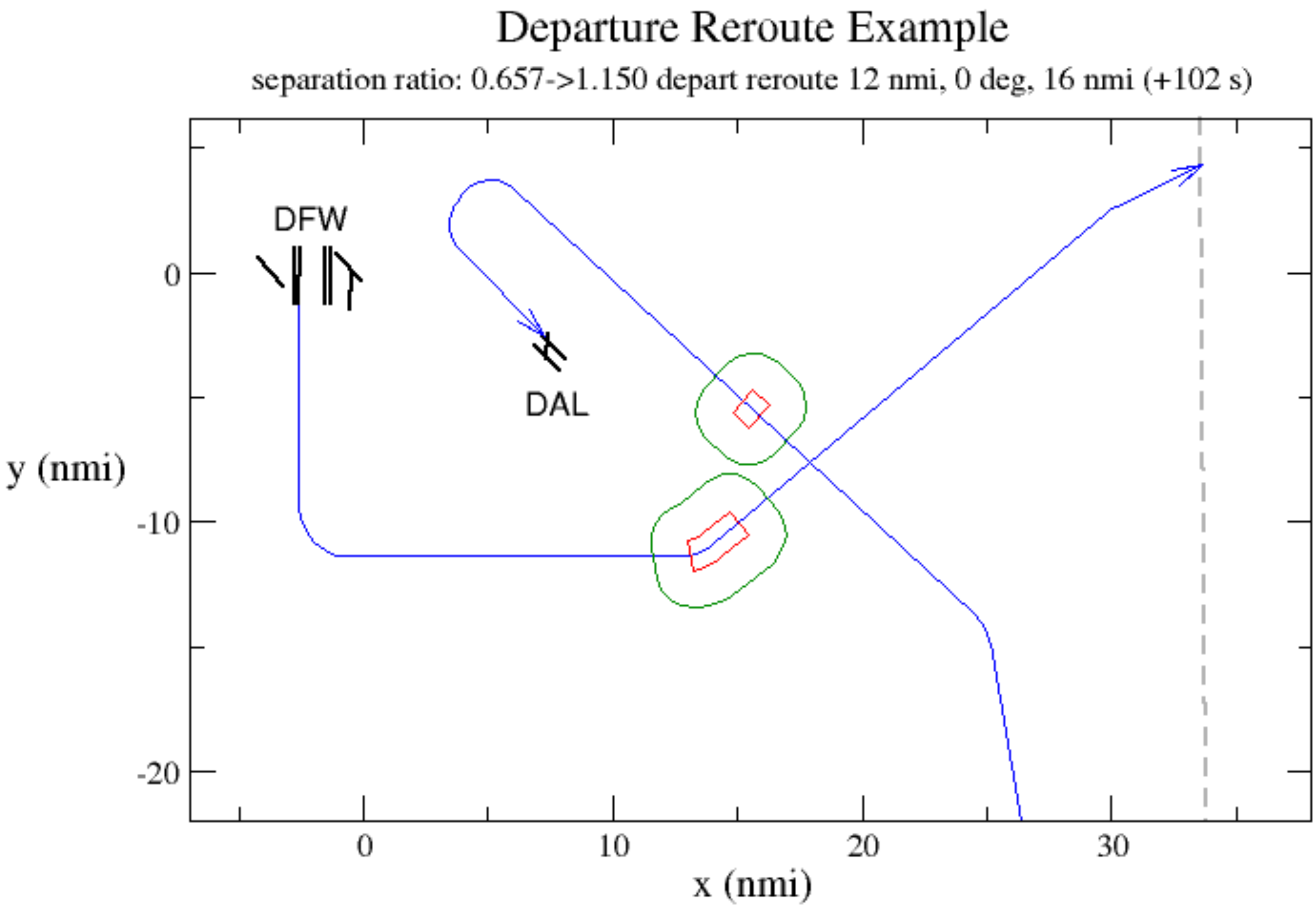

Departure Reroute Example
separation ratio: 0.657->1.150 depart reroute 12 nmi, 0 deg, 16 nmi (+102 s)
DFW
DAL
y (nmi)
0
-10
-20
0
10
20
30
x (nmi)
red rectangle = bounding area (at min separation)
green oval = buffered bounding area (sep = 3 nmi)

Conflict Planview for Departure Reroute Example

separation ratio: 0.657

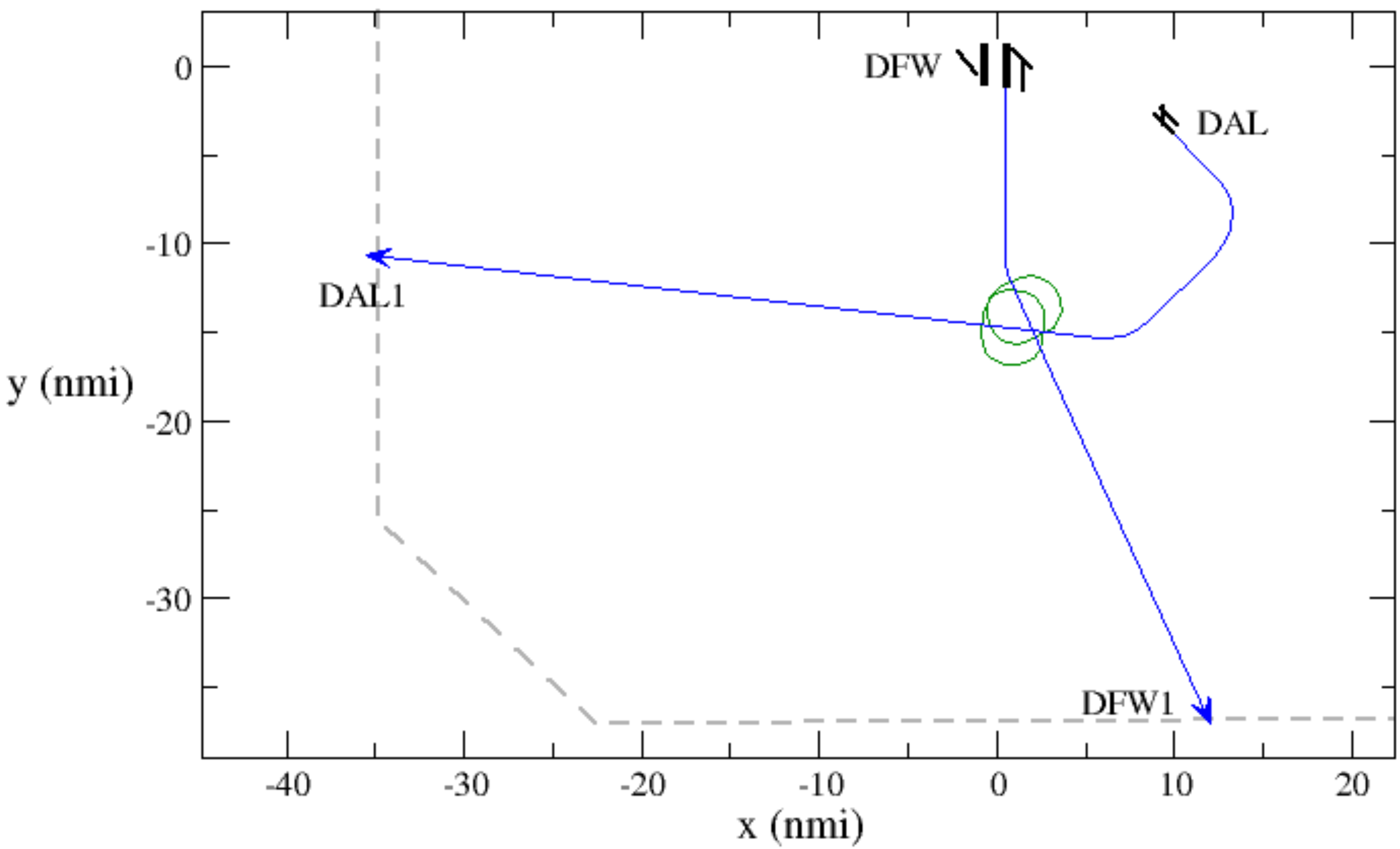


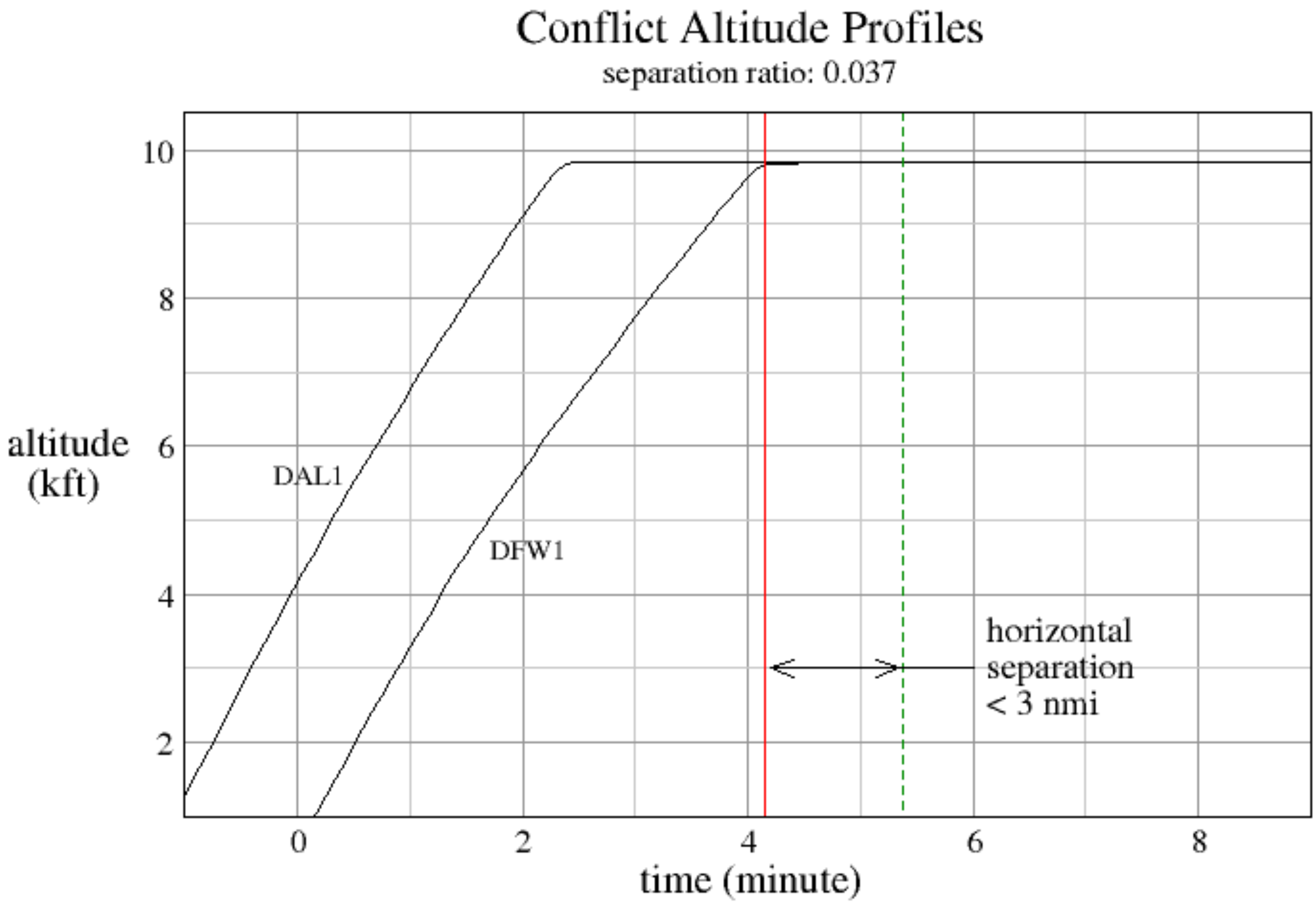

Departure Reroute Example
separation ratio: 0.657->1.150 depart reroute 12 nmi, 0 deg, 16 nmi (+102 s)
DFW
DAL
y (nmi)
x (nmi)
0
-10
-20
0
10
20
30

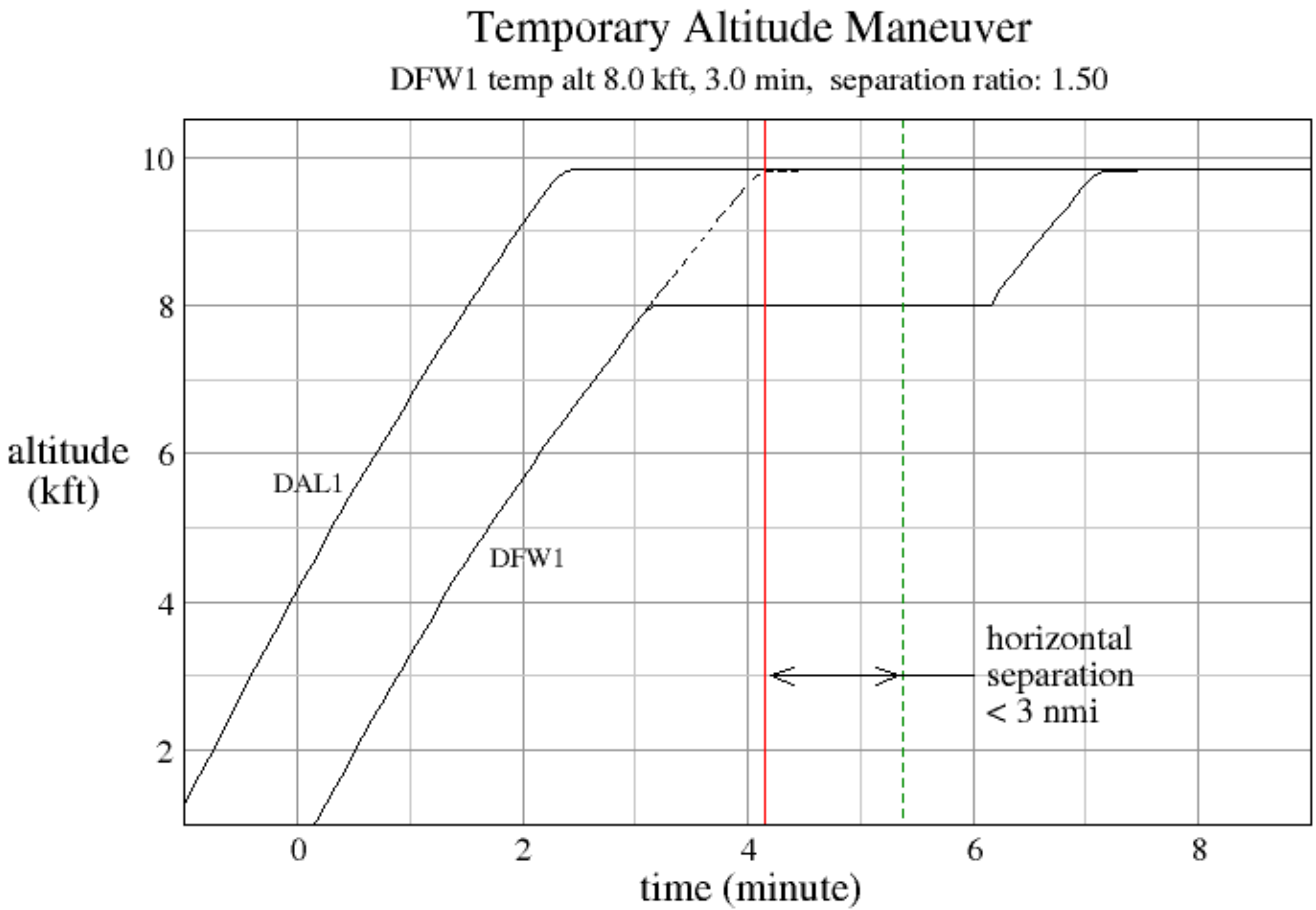

Departure Reroute Example
separation ratio: 0.657->1.150 depart reroute 12 nmi, 0 deg, 16 nmi (+102 s)
DFW
DAL
y (nmi)
0
-10
-20
0
10
20
30
x (nmi)

Conflict Planview

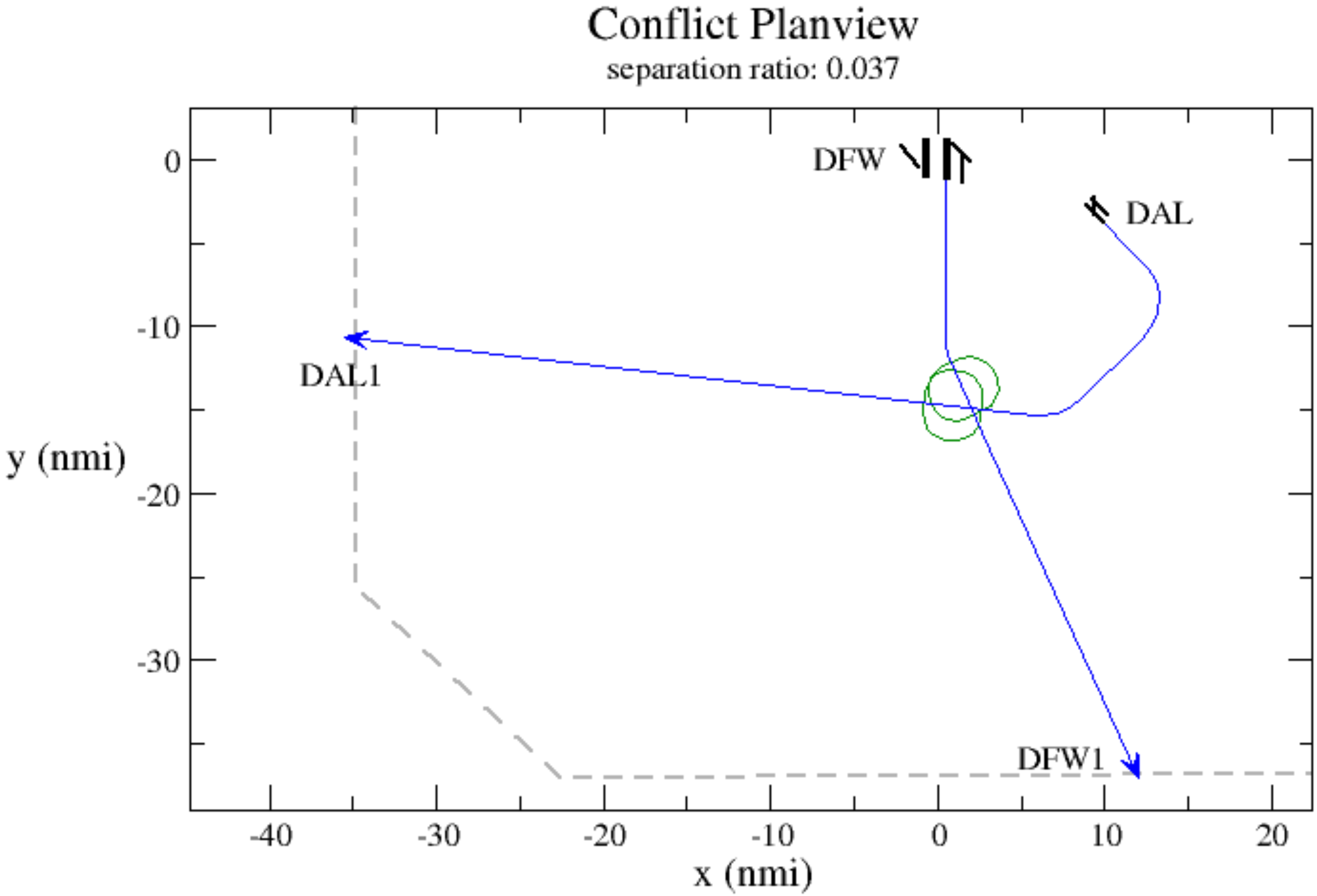
separation ratio: 0.037



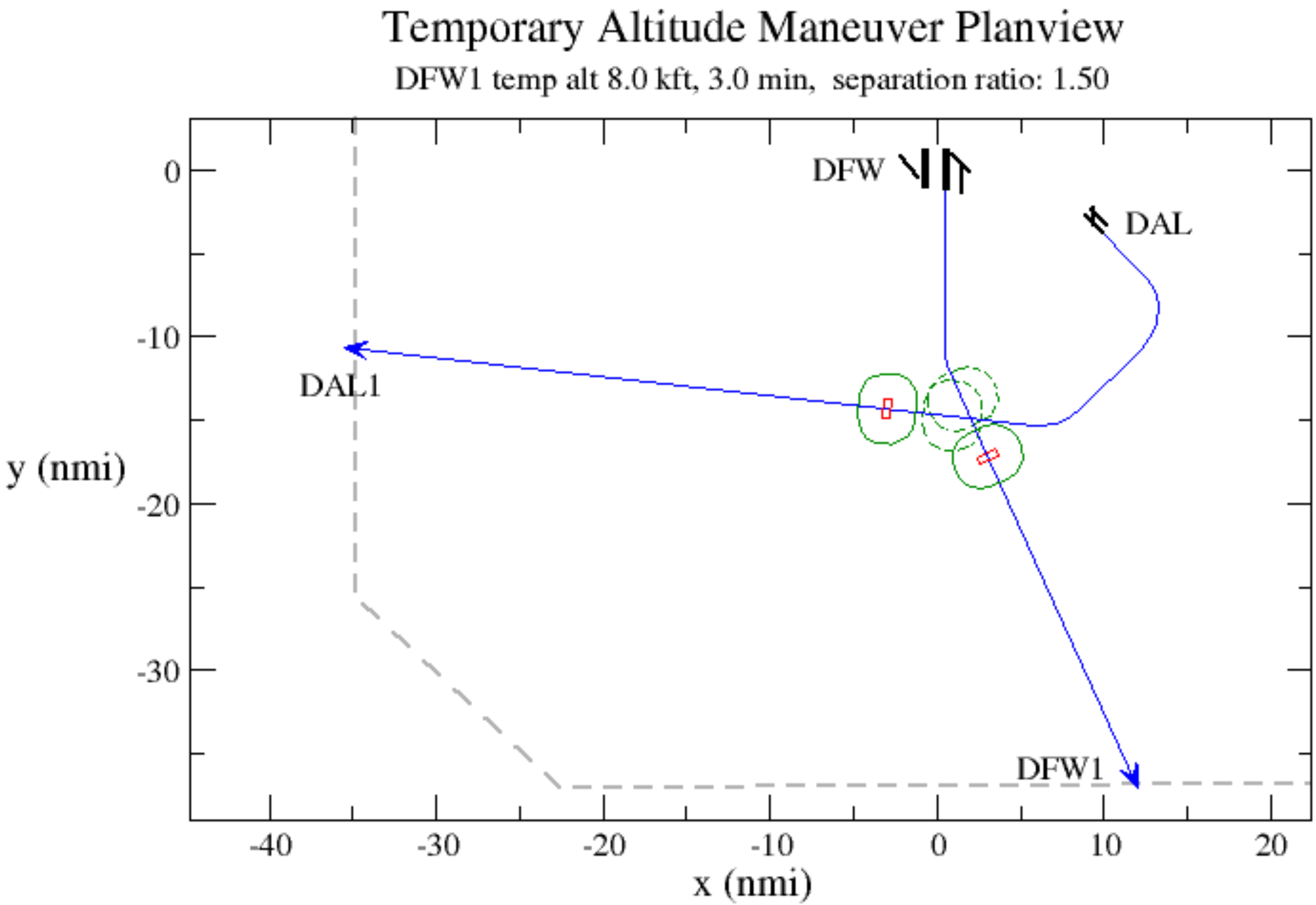

Conflict Altitude Profiles
separation ratio: 0.037
altitude (kft)
10
8
6
4
2
0
2
4
6
8
time (minute)
DAL1
DFW1
horizontal separation < 3 nmi



Temporary Altitude Maneuver
DFW1 temp alt 8.0 kft, 3.0 min, separation ratio: 1.50
altitude
(kft)
10
8
6
4
2
0
2
4
6
8
time (minute)
DAL1
DFW1
horizontal
separation
< 3 nmi



Conflict Planview
separation ratio: 0.037
DFW
DAL
DAL1
DFW1
y (nmi)
x (nmi)
0
-10
-20
-30
-40
-30
-20
-10
0
10
20


Temporary Altitude Maneuver Planview
DFW1 temp alt 8.0 kft, 3.0 min, separation ratio: 1.50
DFW
DAL
DAL1
DFW1
y (nmi)
x (nmi)
0
-10
-20
-30
-40
-30
-20
-10
0
10
20

Concluding Remarks

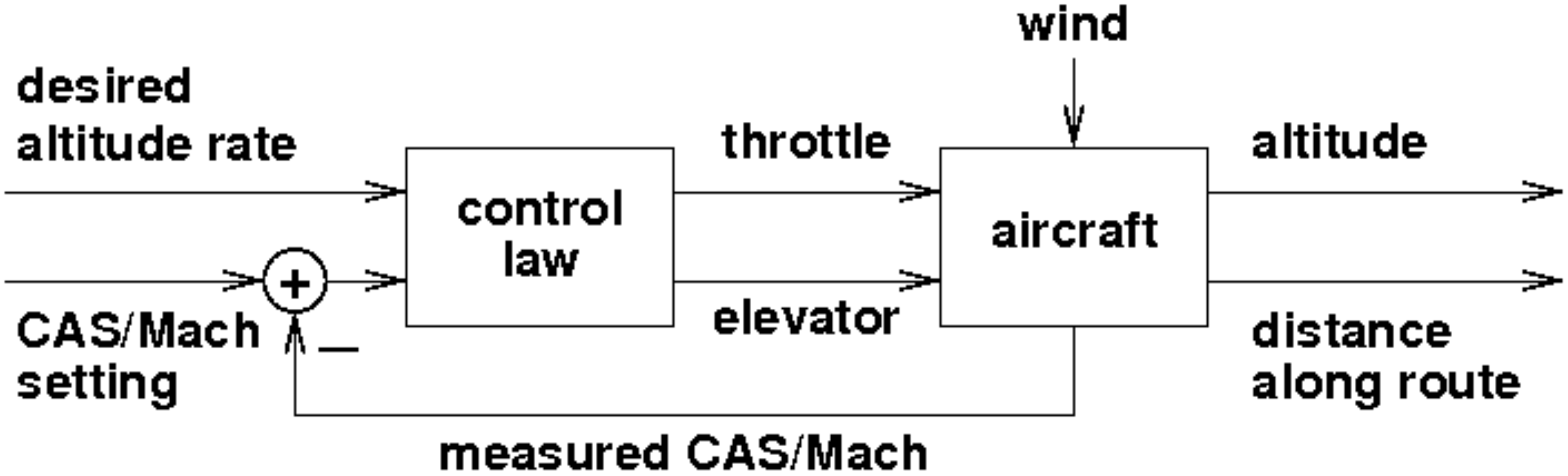
- Trajectory Specification is dynamic “4D” RNP (Required Navigation Performance)
- Each flight constrained to a well-defined volume of space at each point in time
- Tolerances can be as large as current traffic situation permits (without a conflict)
- Makes ATC more failsafe and less dependent on backup systems and tactical maneuvers
- Computational feasibility of pairwise conflict detection and resolution demonstrated

Questions?

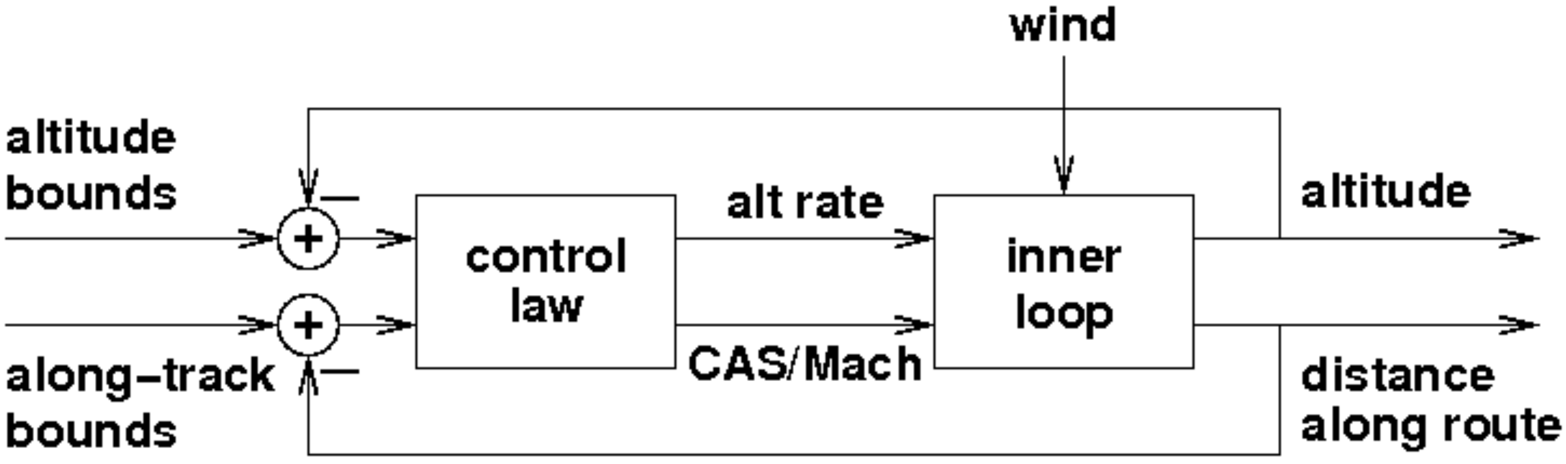
Russ.Paielli@nasa.gov

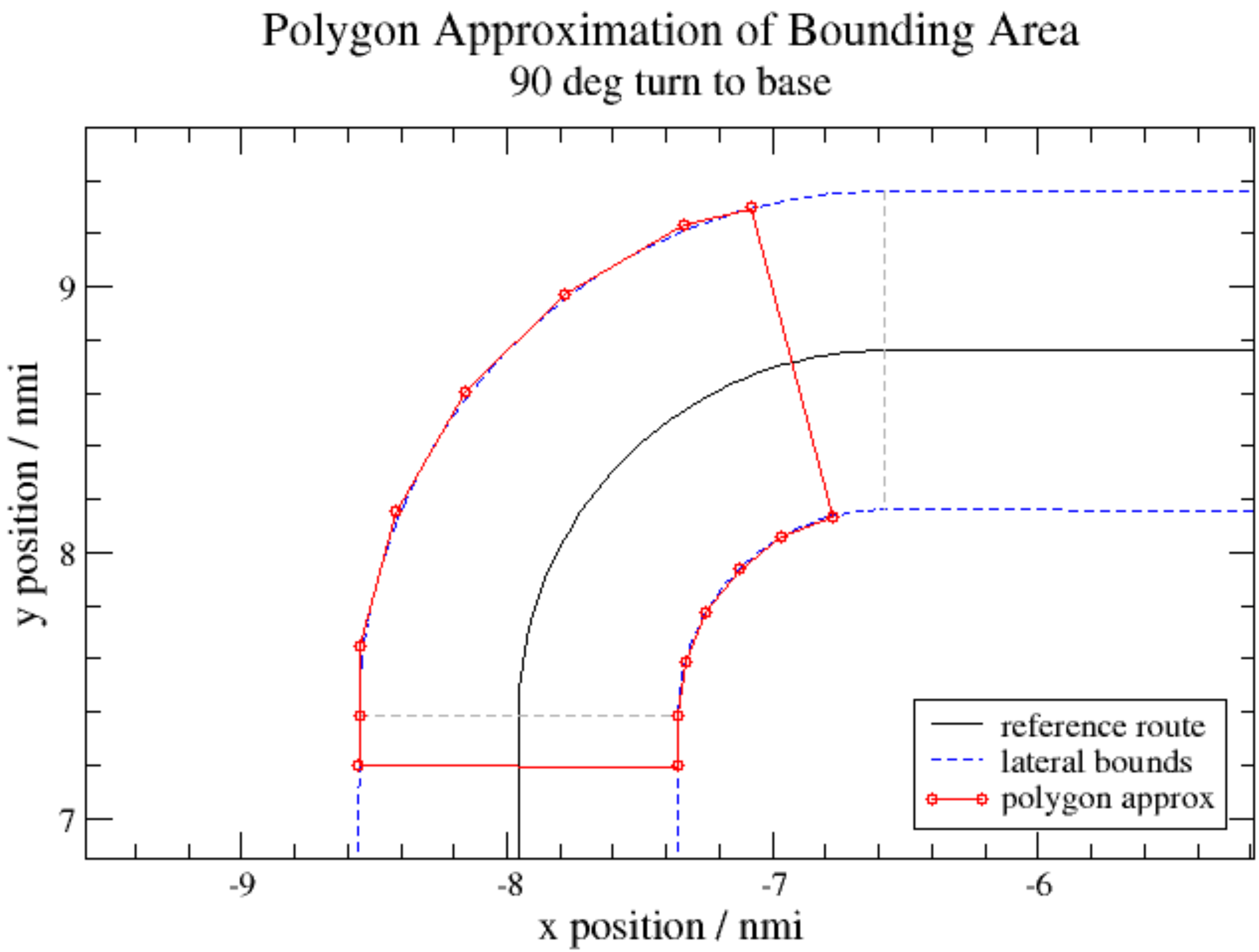
Backup Slides

Simplified Longitudinal Flight Control

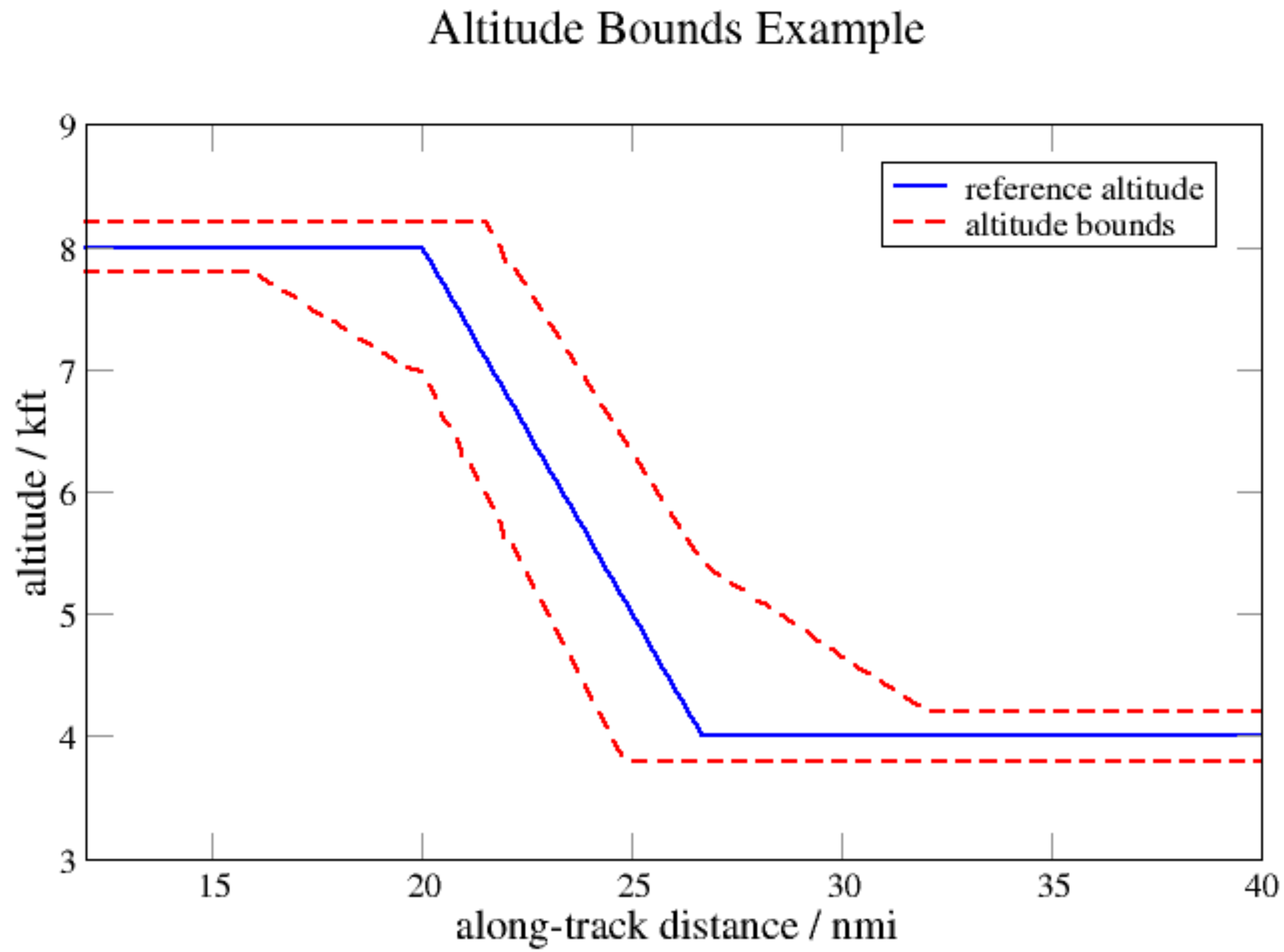


Enhanced Longitudinal Flight Control





Polygon Approximation of Bounding Area
90 deg turn to base
y position / nmi
x position / nmi
9
8
7
-9
-8
-7
-6
reference route
lateral bounds
polygon approx


Altitude Bounds Example
reference altitude
altitude bounds
altitude / kft
along-track distance / nmi
9
8
7
6
5
4
3
15
20
25
30
35
40

Terminal Area Spacing and Separation Requirements

- Terminal areas (airspace within ~40 nmi of a major airport) requires both
  - In-trail spacing for wake vortex (3 – 6 nmi) and
  - general separation (3 nmi lateral or 1000 ft vertical)
- Delay maneuvers for wake vortex spacing also resolve most general separation conflicts
- A proven strategy is to first delay for the necessary arrival spacing, then apply other maneuvers when necessary to achieve general separation

Default Tolerances

- Cross-track: 0.6 nmi constant
- Vertical:
  - Departures: 500 ft constant
  - Arrivals: 500 increasing to 800 ft
- Along-track:
  - Departures: 0.2 increasing to 1.0 nmi
  - Arrivals: 1.0 decreasing to 0.2 nmi

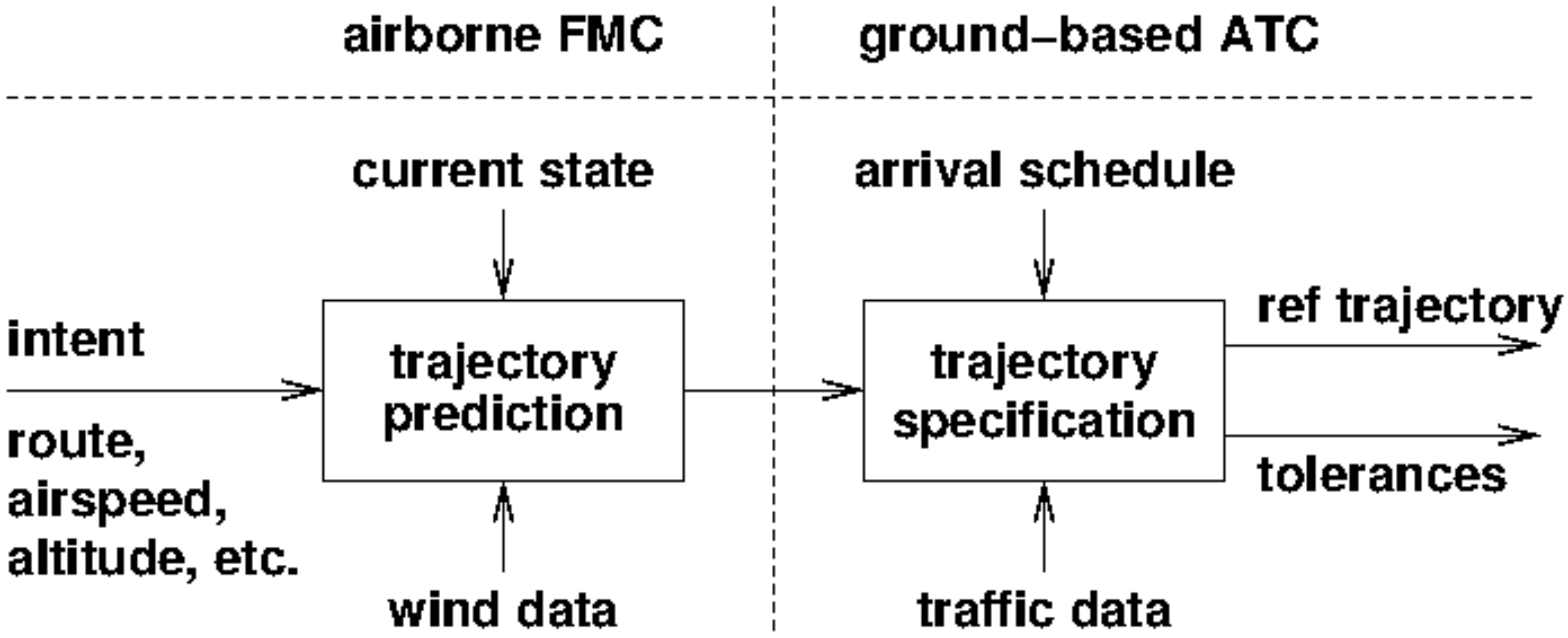
Terminal Areas

- Class B airspace within approximately 40 n. miles (nmi) of a major airport
- Managed in US by Terminal Radar Approach Control facilities (TRACONs)
- Minimum separation standard: 3 nmi horizontally or 1,000 ft vertically
- Have more constraints than enroute airspace and have more and larger turns
- Terminal ATC is currently very tactical, with many heading vectors and speed/altitude clearances
- Throughput limited mainly by wake-vortex spacing requirements (3-6 nmi, depending on weight classes)

Background

- Air Traffic Control (ATC) is currently done by human controllers with radar displays and voice communication
- Controllers are human and make mistakes (over 1,800 operational errors in one recent year, including 55 serious cases)
- Automation can reduce human error and increase airspace capacity but is difficult due to complexity and safety criticality

Trajectory Prediction and Specification



Maneuver Type Counts

maneuvered: other:	arr arr	arr dep	dep dep	dep arr	sum
temp alt	11	245	311	282	849
speed dec	173	0	2	0	175
reroute	55	3	27	79	164
new level alt	5	22	53	11	91
takeoff delay	0	0	40	6	46